INTRODUCTION TO

VALVES

INCLUDING REFERENCE TO

CATHODE RAY TUBES

By

F. E. HENDERSON

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F. E. HENDERSON

A.M.I.E.E.

Osram Valve Department

The General Electric Co. Ltd. of England

A MANUAL INTENDED FOR THOSE WHO, WITH LITTLE OR NO PREVIOUS EXPERIENCE, ARE CALLED UPON TO HANDLE RADIO VALVES AND CATHODE RAY TUBES AND THEIR ASSOCIATED DEVICES

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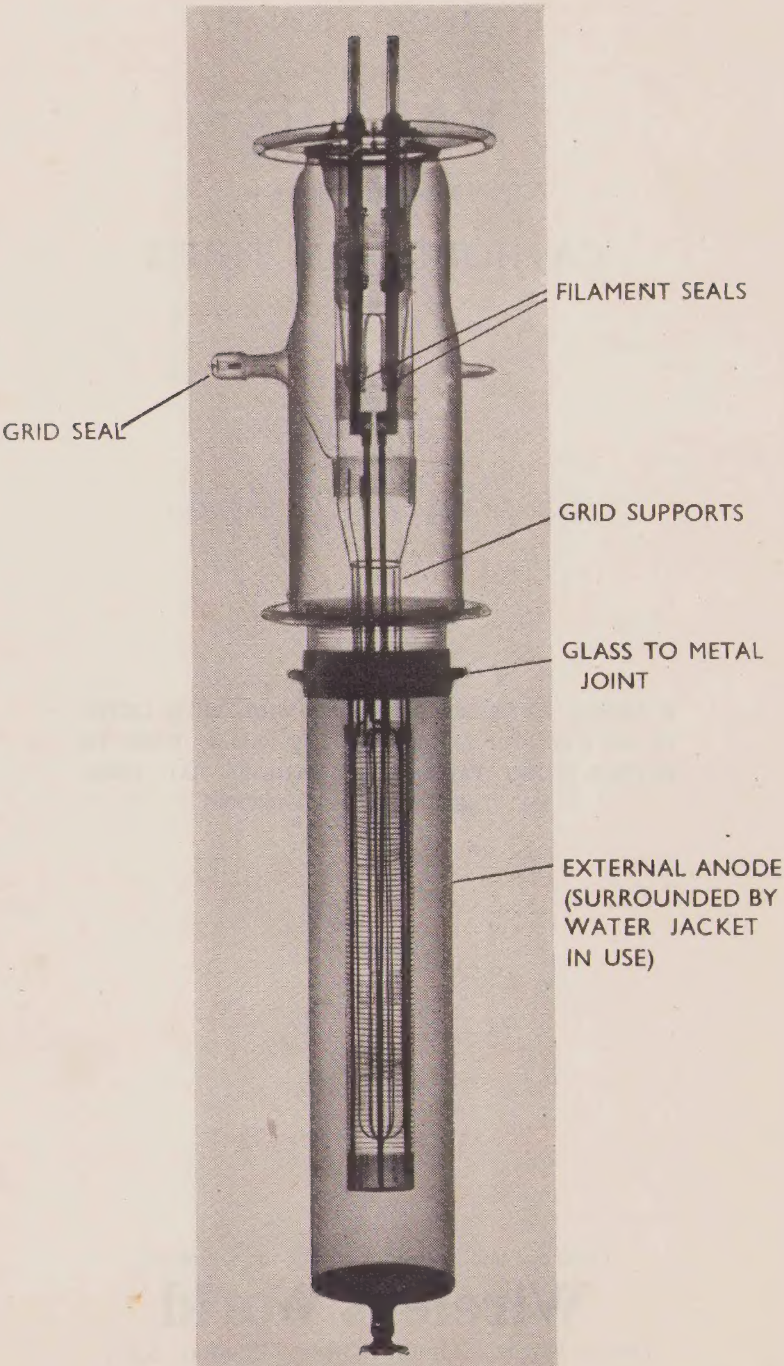

An X-ray photograph of a large external anode type of power triode, showing the disposition of the filament and grid, and the glass-to-metal joint used in this class of valve. In practice the heat dissipated at the anode is conducted away by a circulating water system, and the valve can thus be operated at high power and increased efficiency.

CONTENTS

PREFACE

It was during the war of 1914–1918 that the radio valve first made its appearance as an instrument of practical utility ; since that period the cathode ray tube has also become a tool of considerable industrial use.

At the present time many students of the practical applications of radio are coming into contact with electron devices such as the thermionic valve and cathode ray tube for the first time, and it is the purpose of this manual to provide such students with a groundwork on which more specialised studies may be based. It is assumed that the reader is in possession of a knowledge of the fundamental theories of electricity and magnetism, including the simple formulæ associating the various electrical units.

The applications of the *thermionic valve* are continually increasing in a wide variety of fields. Millions of valves are being employed in communications, both by radio and by line ; their use in industry and in other specialised work is growing day by day. It is obviously not possible in a publication of this scope to do more than outline the general principles involved and the more common applications.

Brief reference is also made to its relative, the *cathode ray tube*, since no radio engineer can afford to be without a working knowledge of this important device ; its application to the visual indication of any physical, mechanical or other operation which can be converted to electrical energy constitutes a specialised study. No attempt is made to deal in greater detail with any aspect of the subject than is sufficient for general working knowledge, but it is hoped that this publication will assist those learning to handle valve or cathode ray apparatus to acquire a better understanding of the principles they are applying.

References and illustrations in this book apply in general to Osram valves and tubes supplied by The General Electric Company, Limited, of England.

CHAPTER 1

The Nature of Electricity : The Free Electron : Thermionic Emission.

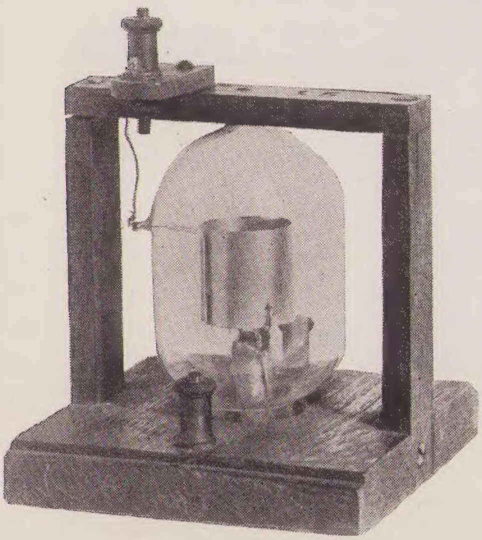

Fig. 1.—An historic valve. One of the very early Fleming diode valves

The effect of the transference of electrical energy has been observed for hundreds of years, but it was not until the nineteenth century that the cause of some of the observed effects became known, and not until comparatively recent years that the theory of the " free electron " began to be discussed and applied.

What is the nature of *electricity?* We know that electricity can be visualised as a dynamic force, and that it only makes itself apparent when a state of electrical unbalance exists between two bodies or parts of a body. In other words, a *potential difference* has to be established between two points before the phenomenon of " electricity " can be observed and utilised.

Fundamental units.

The first result of the setting up of such a potential difference, or *voltage*, between two points is that with a suitable conducting medium, a transference of energy takes place between them. *Power* can be developed, which corresponds to energy expended or work done per unit time. The unit of power is called the *watt*, which is dependent upon two factors : the voltage (or electrical pressure) and the quantity of electrical units per second, or *current* passing between the two points. For a given voltage, the current, in its turn, is dependent upon the *resistance* offered to its passage, and so we have the following three fundamental factors governing any electrical problem :

The *voltage*, or *potential*, or electrical pressure, which is measured in *volts*.

The *current*, or quantity of electricity per unit time, which is measured in *amperes*.

The *resistance* to the transference of current, which is measured in *ohms*.

The relation between the three in D.C. circuits is given by the well-known Ohm's Law,* familiar to every student of electricity.

The transference of electricity may be looked upon from a different angle. Just as nature abhors a vacuum, so she opposes a state of non-equilibrium, and a flow of electric current may be explained by the fact that nature is trying to re-establish a state of equilibrium between two points—something has happened which requires a restoration of the original state of balance. The ancients, observing the effect, did not appreciate the cause, and believed that " electricity " was something to be manufactured and released, whereas we now know that it is intimately bound up with the composition of matter, and that all matter is built up of what may be described as " heavy " and " light " particles which may be considered as units of *positive* and *negative* electricity respectively. Once one or more of these are removed from the atom of matter, that atom will lose its state of balance and will try to restore its original condition by attracting an equal number of the missing component from any possible source.

Closed and open circuits.

Generally, considerable resistance is offered to this restoration of balance, but it can be facilitated by connecting the two points, between which there is a potential difference, with a *conductor*, that is, a material which will permit a flow of electricity. All metals are conductors, some being better in this respect than others. The connection of two points which are at different electrical pressures by means of a metal wire forms what is known as a *closed circuit*, and in this circuit the flow of electric current may be made to give rise to heat, light, magnetic and other effects.

If no conductor is present between the two points they are said to be *insulated* and the material between them is an *insulator*. Examples of insulators are air, ebonite, porcelain, glass and similar non-metallic materials. In ordinary closed circuits, although electric currents may flow round the circuit, they cannot escape from its confines.

A development of immense importance in the history of electrical science was the discovery that the characteristics of electrical energy may be observed and applied in certain conditions *even when no conducting matter* is present. This phenomenon is the basic principle of the operation of the thermionic valve. It was found that if a wire was electrically heated to incandescence, particles of electricity were able to leave the confines of the wire, even if this were placed in an

*See Appendix 2.

evacuated container or bulb, and under certain conditions could be caused to stream across the evacuated space and form an electric current. Such an arrangement is an embryo *thermionic valve.*

The electron.

Scientists have since proved that the electric particles set in motion in the thermionic valve, and similar devices, are all possessed of identical properties, are incomparably lighter and smaller than any atom of matter, and cannot be further subdivided. This means that electricity may be considered in terms of individual particles, each consisting of a unit charge. To this unit charge is given the name *electron.*

The word electron is accepted as describing an incredibly small particle consisting of a charge of what may be termed " negative electricity." Applying this idea to the constitution of matter, it has been proved that a cluster of these electrons is normally revolving in pre-determined orbits around a central positive nucleus, the whole forming an *atom* of matter. (This conception of the electron as a particle of negative electricity is the simplest to grasp, although it should be stated at the outset that the electron sometimes acts as though it were a group of undulations, or " waves," and not as a concrete particle.)

When electron transference is no longer restricted to a closed conducting circuit, we have the phenomenon of the *free electron,* or the liberation of electrons from the confines of an electrical conductor. The " free " electron may appear either as the result of raising a metallic substance to a sufficiently high temperature to liberate the electron, or it may be released under certain conditions even though the temperature of the emitting substance is not changed. The latter condition, which forms the basis of the " cold emitter," sometimes utilises a beam of light to release the electron,* but this does not concern us here, where we are confined to cases in which the quantity of electrons liberated is governed by temperature.

The term given to the liberation of electric particles by heating a conducting material to a sufficiently high temperature is *thermionic emission,* and when this condition exists these charged particles may be either electrons or *ions,* according to the circumstances prevailing, and may be drawn off and controlled by a suitable electric field. The electron (unit of *negative* electrical charge) is lighter and is able to move more freely than the ion (unit of *positive* electrical charge), and in fact, by reason of their negligible mass, electrons are capable both of being moved at enormously high speeds and of changing their speed and direction practically instantaneously. These are the properties which make the phenomenon of electron emission so valuable in practice.

We can now form a picture of the free electron as moving about *within a conductor* at speeds depending on the temperature of the conductor—the higher the temperature the greater the speed of movement. Up to certain velocities the mutual attraction between negative electrons and positive ions prevents these electrons from escaping, and restricts their movement to the surface of the conductor, but as the velocity of disturbance is increased it ultimately becomes high enough to permit a proportion of these jostling particles to pass right through the surface of the conductor and escape. We then have the condition known as *electron emission,* and such freed electrons are in a state to be controlled at will, either in speed or direction.

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*This is known as the photo-electric effect.

CHAPTER 2

Electron Current : The Cathode : The Anode : Composition of the Cathode : Factors Governing Constancy of Emission.

Many years ago, an interesting experiment with a carbon filament lamp led to results of far-reaching importance. A carbon filament lamp, with a direct voltage applied across its filament, had a small metal plate introduced into its bulb, and when this plate was joined by a wire through an airtight seal in the glass bulb to the positive end of the glowing filament, a very small electrical current was indicated by a measuring instrument, such as a galvanometer, placed in series with the external wire (Fig. 2). This showed that a complete circuit was formed, which must have been baffling to the experimenter because part of the circuit consisted of the vacuous space between the filament and the plate inside the lamp, and, as was well known, a vacuum is practically a perfect electrical insulator.

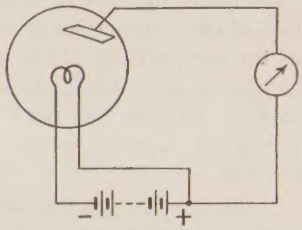

Fig. 2.—Diagrammatic representation of simple electron tube.

By the discovery referred to in the last chapter, of the free electron, these results could be explained as being due to *electron current ;* they were later turned to practical utility and led to the development of the " electron valve."

Electrodes in a thermionic valve.

We have seen that it is possible to produce an electron " cloud " around a conductor by means of thermionic emission, these electrons being imagined as unit charges of negative electricity which can be influenced by the electric field generated around another conductor or conductors close to them. These two or more conductors are termed *electrodes*, and that electrode which is caused to emit the electrons is termed the *cathode*. The electrons, being negative particles, require a positive electric field to accelerate them, and so the cathode is always negative relative to any accelerating electrode.

In a thermionic valve, just as a negative or electron emitting cathode is essential, so is a positively charged electrode, in order to create the necessary electric field and thus attract the negative electron stream. This positively charged electrode is termed the *anode* (sometimes called the " plate ").* The *potential gradient*, or *electric field* between cathode and anode causes the electrons emitted from the cathode to be accelerated in velocity, and by this means they are enabled to travel farther afield and penetrate beyond the area surrounding the cathode surface. The application of a positive potential to the anode may be thought of as a removal, by external means, of some of the electrons from its substance, these electrons being conveyed by means of an external conducting path to the cathode ; the flow of negative electrons towards the anode takes place in an endeavour to restore the balance upset by this transfer, and, so long as external power is applied to create this state of affairs, the electron stream through the valve will exert every effort to restore equilibrium.

In a thermionic valve, therefore, we require two sources of power, separate and distinct from each other ; one to heat the cathode to sufficient temperature to liberate free electrons, and the other to create sufficient difference of potential, or voltage, between cathode and anode to give these electrons sufficiently increased velocity to enable them to arrive at the anode. The cathode very often takes the

*There may be two or more positively charged electrodes in a valve, but for the sake of simplicity, one only is considered at this stage.

form of a fine wire through which an electric current (distinct from our electron current) is passed, with the sole object of heating it, and as such is often referred to as the *filament ;* the cathode and filament are not always the same thing, however, as we shall see later.

Emission from hot cathodes.

The effect of applying heat to the cathode is to cause the electrons within the atoms of the cathode material to be disturbed, and if the temperature is high enough some of the electrons will attain sufficient velocity to reach the surface and with subsequent increase of temperature, will escape as free electrons. (An analogy is that of the evaporation of water molecules from the surface of water, which increases as the temperature of the water is raised.) The temperature required to cause the escape of electrons depends upon the nature of the cathode surface, and so this cathode surface has been the subject of an exhaustive and prolonged study by physicists, because it has such a vital bearing on the efficiency of all electronic devices.

In considering the case in which a wire filament carrying current forms the electron emitter, it must first be appreciated that the temperature gradient along it is not constant—first, because the ends joined to the supports are not as hot as the free central portions, and secondly, because the electron current itself causes an increase of temperature at the end most negative to the anode. Assuming uniform filament temperature, however, the relation of the electron current to the anode-cathode voltage as the latter is progressively increased (anode positive to cathode), may be shown by a curve such as Fig. 3. It will be seen that, as the anode is made increasingly positive, the electron current grows rapidly at first, then less rapidly, and finally remains constant—a further increase in anode voltage producing practically no corresponding increase in current. At this point the electron current is said to be *saturated.* The actual value of current at which saturation takes place depends on the temperature of the cathode (for a given emitting material), and the higher the temperature the higher the value at which the electron current saturates.

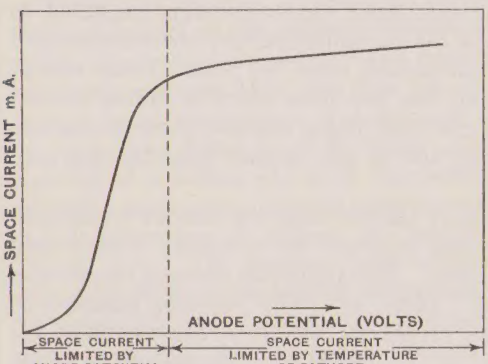

Fig. 3.—*Simple curve relating electron current to anode-cathode voltage.*

We see, therefore, that the current through the cathode-anode space depends first of all on the forces acting on the electrons after they leave the cathode. In addition, the current depends on the quantity of electrons available. The curve (Fig. 4), shows the effect of increasing the supply of electrons from a given cathode by increase of applied filament voltage, causing corresponding increase in the cathode temperature.

The current representing the total quantity of electrons emitted from the cathode under saturation conditions is termed the *emission,* or *total emission* of the cathode. This emission is dependent on two factors—the nature of the cathode material and surface, and the temperature at which it operates. If we assume the simplest case, that of a cathode consisting of a pure tungsten wire filament, a set of conditions can be arrived at whereby we can relate the emission directly to

temperature. The use of " clean " metals as electron emitters is, however, not widely adopted in practice (except for valves handling a large amount of power) owing to the fact that the efficiency—or available emission for a given heat applied—is much lower than for treated, or " contaminated " metals, or for electron-emitting non-metals. In fact, the total emission from a perfectly uncontaminated metal is so small that the temperature required to enable its electron emission to be measured with accuracy approaches the melting point of the metal.

Dull-emitter cathodes.

The story of the application of " contaminated " metals to use as electron emitters is an interesting one. In the early days of the manufacture of tungsten filament electric lamps it was found that when these lamps were run from alternating current, in some of them early filament failure occurred due to the formation of localised " hot spots," and further that this could be prevented by mixing with the tungsten a very small quantity of a metallic oxide called Thoria. Investigation showed that such filaments, after treatment in a high vacuum, were capable of much higher thermionic emission efficiency when this impurity Thoria had been added, and the discovery led to the widespread application of the " thoriated tungsten filament " to thermionic valves.

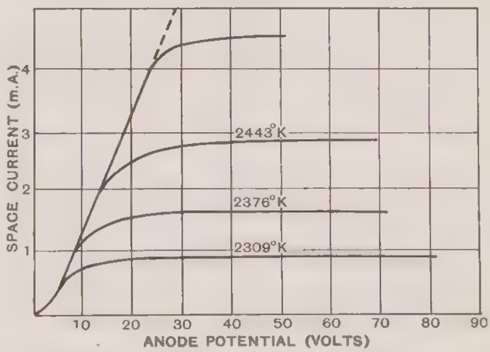

Fig. 4.—Saturation characteristic for tungsten emitter. Curves for degrees absolute.

As such filaments required to be heated only to yellow heat in order to produce their electron emission, in contrast to the pure tungsten filament, which had to be made white hot, the valves employing them came to be styled *dull emitters*, as distinct from those with filaments operating at incandescence and therefore styled *bright emitters*. The dull-emitter thermionic valve is now the only class used for wireless reception purposes, although it actually makes use of other forms of electron emitter to the almost total exclusion of thoriated tungsten.

An important point concerning the subsequent operation of such a filament is that once it has been activated a substantial increase in the normal operating temperature will cause practically complete de-activation, and such a valve is said to have " lost its emission." A dull-emitter valve may therefore have a filament which is quite intact mechanically, but which is useless as an emitter when operating at its rated voltage.

For smaller valves, and indeed, for many modern large valves, a much more efficient emitting surface than thoriated tungsten or simple metallic emitters is used. The most important non-metallic emitters are those in which a central core is coated with an alkaline earth oxide, suitably treated, and so they are commonly known as *oxide cathodes*. Tungsten is not always used as a core, and nickel or copper—especially nickel—are usually the metals employed.

The oxide-coated cathode is in widespread commercial use owing to its high efficiency, and it is interesting to compare its efficiency figures with those of pure tungsten and thoriated tungsten. The efficiency figure is based on the total emission obtainable for a unit of electrical power used for heating purposes :

" Clean " tungsten	1 milliampere per watt
Thoriated tungsten	25 milliamperes per watt
Treated oxide coating	150 to 250 milliamperes per watt

Thus the oxide coating represents an improvement of up to ten times that of thoriated tungsten, and 250 times that of pure tungsten.

Factors determining the "life" of a dull-emitter cathode.

Two factors are essential for the maintenance of good "life" performance with oxide cathodes; the first is that the operating temperature is more or less critical and therefore the *filament voltage must never exceed the maximum permissible for the type.* In this the oxide cathode is at once both similar to and different in some respects from the thoriated filament in the results of overrunning—similar because an increase in temperature will in both cases destroy the "dull-emitting" properties of the emitter, and different because, whereas in the thoriated filament the emission may usually be renewed by re-treatment, the oxide coating is in almost every case rendered permanently inactive.

The second factor is the extreme importance of preventing "poisoning" of the cathode by the presence of undesirable gases—principally oxygen—within the bulb.

Although, as we shall see,* some gases or vapours are innocuous and deliberately introduced for various reasons, the prime endeavour of manufacturers is to attain and maintain as high a degree of vacuum as is commercially practicable within the valve bulb or envelope. The success of oxide-coated dull emitters is found to be entirely dependent on the freedom from contamination by gases or water vapour of the emissive layer. Harmful gases may come from the walls of the envelope, or from the metals of the electrodes themselves, and therefore precautions are taken in manufacture to "bake" the glass envelope and "vacuum-furnace" the electrodes in order to drive off any occluded gases.

A method of "cleaning up" gas within the envelope following the usual pumping process is the use of a "getter," and all small thermionic valves used for radio reception or amplification make use of this device. A *getter* is a layer of some substance that will absorb gas, and it is deposited on the inside of the envelope. Valves which have undergone the "gettering" process usually have parts of their bulb blackened or "silvered" on the inside, due to the deposition of the getter material.

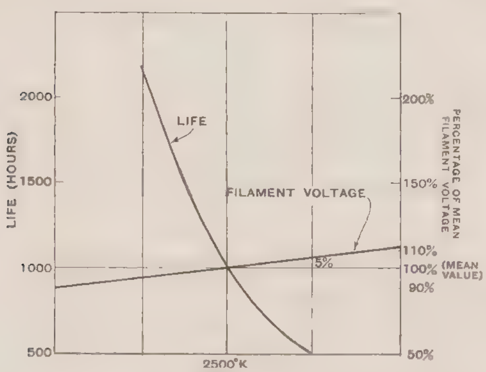

Fig. 5.—Effect of filament voltage on life (bright emitter tungsten filament).

Generally the metal of which the getter is composed is packed inside a container, which is welded to one of the electrodes of the valve, or a support wire, and application of heat during the evacuation process volatilises the getter, which condenses on the walls of the bulb. Usually the getter is "directed" in order to avoid precipitation on parts of the electrode assembly which might as a result develop electrical leakages and hence noisy operation.

In order to conserve the life of a dull emitter thermionic valve, that is, to ensure constant and lasting electron emission, there are certain points regarding its operation which are essential, and should be carefully observed.

*See chapter 12, on Gasfilled Rectifiers and Relays.

In the case of a clean tungsten, or bright emitter filament, the life (providing the vacuum is maintained) is a function of the filament temperature, being determined in this case by ultimate fracture, or " burn out," and not by loss of emission. For filaments running normally at incandescence a rough estimate is that an increase of 5 per cent in filament voltage will halve the life of the valve (Fig. 5).

In the case of a dull emitter filament—particularly one of the oxide-coated type—the life is dependent on a large number of factors. Again, however, a point of major importance is the operating temperature of the cathode or filament, which is controlled by the applied voltage ; this must not be increased beyond a small percentage (the tolerance being necessary to allow for normal fluctuations of supply voltage). The extent to which the voltage may be *reduced* below the safe maximum depends on the application ; in cases where very little emission is required in use, the operating temperature can be considerably lower than in other valves (such as power valves and rectifiers) from which are constantly drawn very large peaks of emission during life. In such valves the extent to which the applied filament voltage may be allowed to fluctuate in the lower direction is often limited, although the cathodes are usually designed with a more generous surface area to allow for normal and unavoidable fluctuations such as those commonly encountered in public supply mains.

The operation of power rectifiers will be dealt with in more detail in the next chapter.

CHAPTER 3.

THE VALVE IN PRACTICE : THE SIMPLE DIODE : FUNDAMENTAL CHARACTERISTICS : VALVE RECTIFIERS : FILTER CIRCUITS : VOLTAGE DOUBLING.

We saw in chapter 2 how a galvanometer needle can be deflected when one terminal is joined to a metal plate sealed into an evacuated vessel containing also a glowing filament heated by direct current, and the other terminal is joined to one

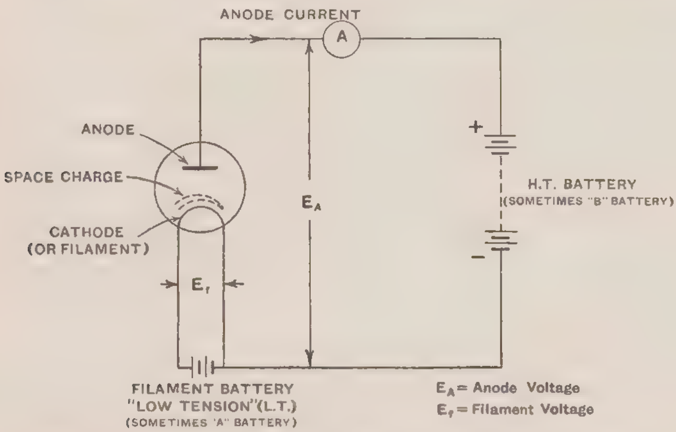

Fig. 6.—Diagrammatic representation of simple diode in circuit.

end of that filament. The first significance of this demonstration was that a closed electric circuit had evidently been formed, even though part of the circuit consisted of the vacuous space between filament and plate. A second point—later to prove of immense importance—was that this closed circuit was formed, or in other words, the vacuous space became a conductor, *only when the metal plate was*

connected to the positive end of the filament. The current through the galvanometer in the external circuit could be started or stopped, depending upon whether the plate had a positive potential relative to the mean potential of the filament or not.

It is this uni-directional property which gives such a device its name—a *valve.* The application and removal of the positive plate potential acts as a " gate " which allows the electron stream to flow in one direction only, always assuming that the envelope contains no trace of gas. The simplest valve is that containing the two electrodes as above, namely a cathode and a plate, or anode, and a valve so formed is called a *diode* (Fig. 6).

Operating voltages of simple diode valve.

The electron stream, released by the cathode and impelled towards the anode, may be controlled or deflected, but in all elaborations the fundamental principle remains the same; the main essential is that the plate must be maintained at a sufficiently positive potential relative to the cathode to overcome the natural resistance to the flow of electrons, and several ways of providing this potential difference are to be found in practice. Although a small electron current can be produced if the cathode consists of a filament heated by a direct current (thus making one end positive to the other) and the plate is connected to the positive end of the filament, this current is very often too small for practical use, because the potential difference, or voltage, between plate and cathode is insufficient to provide adequate accelerating force within the valve. It is therefore necessary to introduce a higher potential difference by some external means. The means adopted vary with circumstances, but the effect is always the same; a common method is to use a primary or secondary battery of cells which is considerably higher in overall voltage than that required to heat the cathode, and which, in view of this higher voltage, is often termed the *high tension battery*, or *H.T.* This distinguishes it from the battery used to heat the filament, which is called the *low tension battery*, or *L.T.* The connections of these batteries are shown in Fig. 6. The potential difference existing between the plate, or anode, and the cathode, is termed the *anode voltage* (E_A). The potential difference existing across the filament or cathode if this consists of a filament, is called the *filament voltage* (E_F).*

In a simple diode valve, the principal requirements are that the filament voltage shall be sufficient to enable the cathode to produce an adequate supply of electrons, and that the anode voltage shall be adequate for these electrons to be impelled across the vacuous space and through the external circuit. The impelling force within the valve is necessary to overcome the electric field surrounding the cathode, and containing a large quantity of negative electrons, this field of negative electrons being called the *space charge.* If no other force existed these electrons would tend to prevent other electrons leaving the cathode, establishing a condition of equilibrium between the pressure of the electrons being emitted and that of those which form the space charge. It therefore becomes necessary to overcome this state of equilibrium and neutralise the effect of the space charge, which is accomplished by the exertion of the positive electric field provided by the anode. Once this is established, the electron stream may be further modified by alteration of the anode voltage or, as we shall see later, by the electric fields produced from additional electrodes within the valve, or by the presence of gas. The electron stream produced by the field of the anode is called the *space current*, or more commonly, the *anode current.*

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*In some cases the filament voltage is known as the " A " voltage, particularly in America. The anode voltage is then called the " B " voltage.

Characteristics of diode.

The resistance offered to the flow of the anode current is commonly known as the *anode impedance* or *internal resistance* of the valve, and this depends upon the anode voltage and the relative geometrical dispositions of the anode and cathode. A typical relationship between the anode current and the anode voltage is shown in the curve of Fig. 15 on page 20. From this it will be seen that the relationship is never quite linear, although for the higher anode voltages it becomes very nearly so. We cannot therefore apply Ohm's Law to arrive at the internal resistance of a valve, and this can only be determined by taking the ratio of a very small *change* in anode voltage to the resulting very small *change* in anode current, since over a very small length the curve is virtually a straight line.

The "impedance" of a valve is therefore not a pure resistance, but is more correctly described as a "differential resistance." Expressing the relationship mathematically, we have:

Anode impedance (or internal resistance) $= \frac{\delta E_A}{\delta I_A}$, where δE_A indicates a very small change in anode voltage, and δI_A indicates the resulting change in anode current in *amperes*.

Generally the anode current is so small that the measurement is made in milliamperes, or thousandths of an ampere, in which case the internal resistance becomes $\frac{\delta E_A \text{ (volts)} \times 1{,}000}{\delta I_A \text{ (milliamperes)}}$.

Rectifiers and "Detectors."

Let us now consider the practical application and limitations of the simple diode. Its function is usually the conversion of alternating voltages applied to it, to produce a uni-directional output. When a valve functions in this manner it is said to be behaving as a *rectifier*. A diode valve is normally limited to this function, for which it makes use of its uni-directional properties to pass anode current only when the anode voltage is positive. Then the effect of rapidly changing the polarity of the anode voltage—as in the case of an applied alternating voltage between anode and cathode—is to produce a series of pulses of current through the valve and external circuit. When the anode voltage is positive, a pulse of current passes through the valve; when it is negative, no current flows in this way.

When the applied alternating voltage is of a low order, or is of low frequency, there are mechanical and chemical methods of rectifying it to produce the desired direct current, but where the voltage or the frequency is high, more particularly the frequency, the advantages of the thermionic valve over all other rectifying devices become over-riding, and for rectification of the frequencies normally used in "wireless" transmission, the valve is supreme. In such a capacity it is known as a *detector* of radio signals.

Space does not permit detailed consideration of the essential characteristics of radio transmission, and a knowledge of the principles of amplitude-modulated radio telephony must be assumed.*

In the case of amplitude-modulated continuous waves used in radio telephony we have a continuous series of high frequency waves of varying amplitude being radiated from the transmitting aerial, this variation being caused by the impression of audio frequencies on the "carrier" H.F. wave. This is known as *modulation* of the H.F. wave, and the depth or degree of modulation is usually expressed as a

*Frequency-modulated signals involve different considerations in methods of detection, but it is not intended to deal with these here.

percentage (see Fig. 7). It is for the process of *demodulation*, or the recovery of the audio frequency signals, that the rectification properties and rapidity of response of the thermionic valve become of first importance, and this subject will be referred to again later.

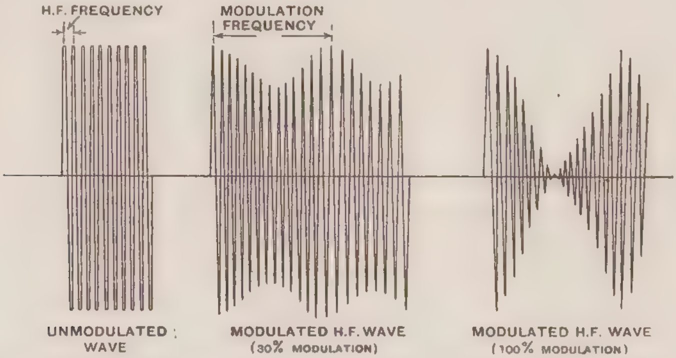

Fig. 7.—Illustrating amplitude modulation of " carrier frequency."

Power rectification.

In its application to *power rectification* of alternating supply, the principle is the same as for the demodulation of wireless transmissions, but there are certain basic differences met with in practice. Thus, the voltage applied may be very considerable, from 100 volts up to 10 or even 100 kilovolts, while the frequency is usually of the order of 50 or 100 cycles per second only. Again, the rectified current required to be delivered in the external circuits may vary from a few milliamperes to several amperes, which calls for extremely generous electron emission from the valve cathode.

Fig. 8(a).—A typical double diode for biphase rectification —Type U14.

One of the principal requirements in a power rectifier is that during the positive half-cycle of the applied alternating voltage,* when the valve is in a conducting state, the impedance or internal resistance of the cathode-anode path shall be low. This is because the voltage across the rectifier in the conducting phase must be small in relation to that across the external circuit. If the ratio of the valve resistance to the external circuit resistance were very high, then a large proportion of the peak voltage would be developed across the valve itself, and consequently the power expended in the valve would be high.

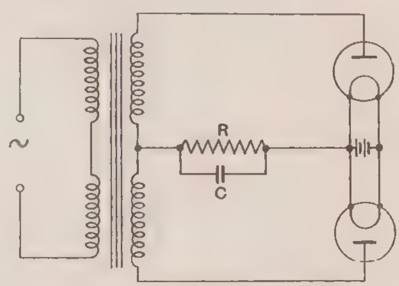

Fig. 8.—Two diodes in a circuit for half-wave biphase rectification.

*Called the " forward " voltage. The voltage in the negative half-cycle, that is, when the anode is negative with respect to the cathode, is referred to as the " reverse " voltage.

In extreme cases, such as a short-circuit of the external circuit, which in this connection is called the *load*, this would tend to overheat the rectifying valve and greatly to shorten its life.

If a single diode such as we have been considering is connected across an alternating voltage it will pass current only on the positive half-cycles of the A.C. wave ; with a perfect rectifier, the negative half-cycles are entirely suppressed, and no current flows. This is termed *single phase half-wave rectification.* A more efficient method is to utilise two diodes so connected that, while one is rectifying, the other is idle, and vice versa. Thus each diode rectifies alternate half-cycles of the alternating voltage, the rectified currents being combined in the output. This is termed *biphase half-wave rectification* (Fig 8). A combination of both diodes in one envelope is common, and in this form the action is identical to that of two separate diodes, being as before biphase half-wave. [An example of this type of valve is shown in Fig. 8(a)].

Filter circuits.

We have seen that a rectifier produces a series of pulses of uni-directional current, and in practice these require to be smoothed out before they can be

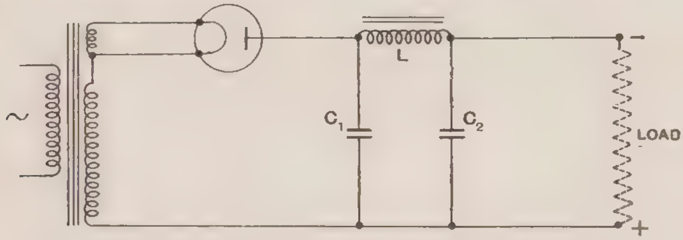

Fig. 9.—Smoothing circuit for rectifier with condenser input.

employed. It is normal, therefore, to provide a *filter* or *smoothing* circuit. The smoothing circuit performs two main functions :

(1) To prevent modulation of the rectified current at a low frequency (either equal to or twice that of the A.C. input frequency).

(2) To increase the rectifier efficiency.

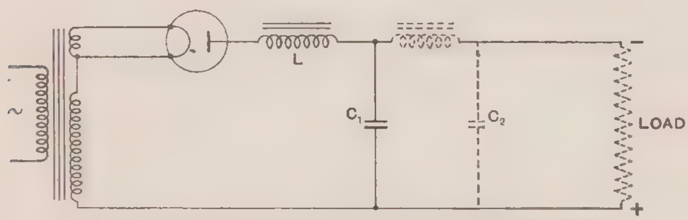

Fig. 10.—Smoothing circuit for rectifier with choke input.

The smoothing filter may take either of two forms :

(1) With a condenser input across the rectifier valve (Fig. 9).

(2) With an inductance (choke coil) or resistance input (Fig. 10).

With a condenser input filter, such as described, it is important to remember four things :

(1) The first condenser (i.e., that immediately across the rectifying valve) influences the peak emission required to be delivered from the valve

cathode. It acts as a reservoir to supply current during the period when the valve is non-conducting.

(2) As it is an essential requirement to maintain a high emission reserve in the rectifier, it is important to maintain the filament voltage at its rated value for adequate cathode emission.

(3) The second condenser (i.e., the condenser across the load) removes the last traces of ripple and has practically no influence on the mean D.C. output from the rectifier.

(4) The choke itself has no great effect on the mean D.C. output or on the current taken from the rectifier, except that it improves the smoothing.

Turning to the second case, that of an inductance or resistance input, we no longer have the onerous condition imposed by a condenser across the rectifier, as the inductance or resistance serves to limit the peaks of current, which in the former case are accepted in full by the condenser. An inductive or resistive input filter circuit is therefore of value where higher mean currents are required to be drawn from the rectifier, but it has the disadvantage of being less efficient by reason of the drop in voltage across the initial choke or resistance. Thus, with such a filter the output voltage across the load will be lower than before unless the applied A.C. voltage across the rectifier is increased. Since in the case of an inductive or resistive input the wattage in the valve is lower than with a condenser input, it is usually safe practice to allow for a higher input voltage, which compensates to some extent for the extra loss in the smoothing circuit. Curves in Fig. 11 show the difference in output characteristics for a given biphase half-wave rectifier with choke and condenser input filters.

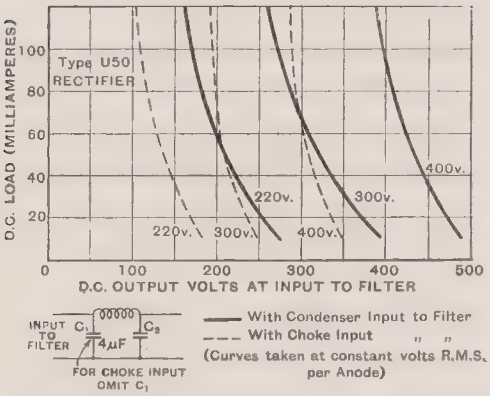

Fig. 11.—Comparison between choke and condenser input filters.

Voltage doubling.

In another form of rectification two rectifier valves (or two single diodes in a common envelope, but with separate cathodes) can be arranged to provide double

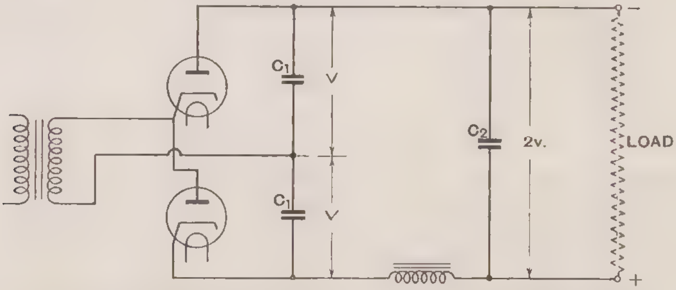

Fig. 12.—Two diodes arranged in a voltage "doubling" circuit.

the voltage output of a single valve. This is known as *voltage doubling*. A circuit is shown in Fig. 12 in which two separate valves are employed, but the same circuit

applies also to a single biphase half-wave rectifier with independent cathodes. The two diodes, or two halves of the biphase rectifier, are connected so that one is reversed electrically with respect to the other, and a double condenser input filter is used. This is so arranged that, during the half-cycle in which one diode is passing current, the condenser across the other diode is discharging through the load and the conducting diode. The voltage across this condenser is therefore added to the rectified voltage across the conducting diode and thus the total voltage across the load circuit is double that obtainable from a single diode. In this type of circuit the " regulation " is poor, that is, the voltage output varies considerably with the amount of current drawn, and so the values of smoothing condensers C_1 must be increased above normal. With filament cathodes it is essential for each to be insulated from the other, or, in other words, a separate heating supply must be provided for each.

Precautions to be observed when operating vacuum power rectifiers.

(1) The cathode should never be allowed to drop below its normal temperature for adequate emission—in other words the voltage fluctuation (inevitable in practice) should be so arranged that the variations from mean value in a downward direction are as small as possible. It is usually safer slightly to *over-run* a rectifier filament, or cathode, than to take the risk of seriously under-running it.

(2) Variations in output voltage should never be made by dimming the filament, but may be made as follows :

- (a) By tappings in the A.C. transformer secondary winding feeding the rectifier.
- (b) By the use of a fixed or variable high resistance in series with the load.
- (c) By the use of a potentiometer, or voltage divider, across the valve output. In this case the total current taken by the potentiometer and the load must not exceed the maximum safe rectified smoothed current rating for the valve.

Considerably greater care is required in operating rectifiers containing gas or mercury vapour, which will be referred to later.

CHAPTER 4

Control of the Electron Stream : Triodes : Secondary Emission.

In a diode, which we have already considered, we have the thermionic valve in its simplest form, in which it is limited to one function, namely rectification of an applied A.C. voltage. In the diode there is no intentional control of the electron emission, which serves merely as a carrier of uni-directional pulses of current.

The discovery that the electron stream could be controlled, marked the starting point for the wide application which the thermionic valve now finds. The flow of electrons from the cathode may, on its way to the anode, be controlled either by electromagnetic or by electrostatic means ; for instance, it was discovered that a bar magnet held close to the electron stream can deflect the electrons from their straight path to the anode, the direction of deflection depending upon the polarity of the adjacent magnet. Similar results can be obtained by the introduction of electrostatic charges on wires or plates close to the electron stream. Electrostatic control is that which is commonly used in valves to-day on account of the ease in which the control can be applied, and the absence of power required in exercising the control.

Triodes. Operation of the grid.

The most familiar method of control of the electron stream involves an additional electrode which, from the form taken by the early examples, is termed a *grid*. The introduction of a control grid constitutes a third electrode within the envelope and the 2-electrode diode now becomes a *triode*, or 3-electrode valve, shown diagrammatically in Fig. 13.

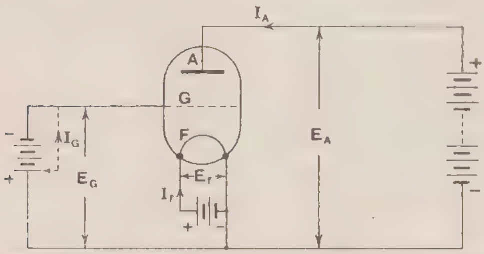

Fig. 13.—Diagrammatic representation of triode, with commonly used symbols.

The control grid normally consists of a mesh or spiral of wire in close proximity to the cathode, and it has applied to it a voltage relative to the cathode which, by reason of the electric field it produces around the grid, exerts an accelerating or retarding force on the space charge current emitted from the cathode. Thus, a positive potential (in relation to the cathode) applied to the grid will accelerate the electrons escaping from the cathode so that more can penetrate beyond the confines of the space charge and ultimately arrive at the anode, and negative potential on the grid will retard the electrons by repulsion so that fewer will attain sufficient velocity to escape from the space charge influence.

The function of the grid is therefore to exercise control of the anode current, and the manner in which it does this depends on a number of factors. It must be

Fig. 14(a).—Typical 2-volt battery triode—Type HL2.

Fig. 14(b).—Typical A.C. heated triode—Type MH4.

assumed at this stage that we have a perfect vacuum within the valve envelope; in other words, the valve is "hard pumped." Were it to contain gas, the effect of the grid would be completely changed. This is dealt with later in the chapter on Gasfilled Valves.

The cathode operating conditions must be such that the anode current is not affected by increase in cathode temperature or applied voltage, nor by its decrease within reasonable limits dictated by fluctuation of supply. The anode voltage is fixed, and the sole control of anode current is that exerted by the grid.

The grid, were it at a positive potential relative to the cathode, would act as an anode and draw electrons to itself, thus establishing a grid-cathode current external to the valve, known as *positive grid current*. This condition would necessitate the expenditure of power in the grid circuit. In most small receiving valves no provision is made for any appreciable development of " power " in the grid circuit and hence in such valves arrangements are made in the circuit so that, although the grid voltage may vary about a mean value, at no time is it permitted to become *continuously positive* in relation to the cathode. (" Positive " grid current should be distinguished from " negative " grid current, which arises from different causes.)

In vacuum valves, the number of voltage fluctuations per second, or the frequency range within which anode current control may be exerted, is for all practical purposes limited only by the external circuit. Owing to the negligible mass of the electron, it may be accelerated, retarded, or reversed in its path millions of times a second if desired ; it is this feature which gives to the valve its invaluable application to radio frequency circuits.

Figs. 14(a) and 14(b) show typical small triodes.

Secondary emission.

To ensure complete control of the anode current by grid voltage, it is necessary that the sole source of electron emission should be from the cathode. While normally this is substantially the case, circumstances can easily arise, due either to the design of the electrodes or to the relative voltages applied to them, wherein both the anode and the grid can themselves become sources of electron emission. This emission, to distinguish it from the primary electron stream released from the cathode, is termed *secondary emission.**

Secondary emission is the result of bombardment by high velocity ions or electrons, and if the surface of the bombarded metal be of such a nature as to release electrons easily, the secondary electron current may be considerable and may seriously affect the functioning of the valve. Secondary emission from the walls of the glass bulb has the effect of reducing the internal resistance at high frequencies, while the introduction of electric charges in the bulb will often cause trouble. Means can be taken to overcome these effects by coating the interior surface of the bulb with a metallic conductor, joined to the cathode, or with carbon. The latter gives the " blackened " appearance common in many modern types of valve.

When secondary emission takes place from the grid, the effect is to cause the production of " negative " grid current, and in practice means are taken, by treatment of the grid wires and by facilitating cooling of the grid system, to minimise grid emission. The only method which can be relied upon to prevent emission from the grid is to keep its temperature as low as possible, and to this end the grid is often fitted with heat radiation fins. The anode may also be made of mesh instead of sheet metal to prevent the grid becoming overheated by reflected radiation.

Secondary emission will be referred to again when we deal with pentode valves in chapter 9.

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*Utilised in valves known as " electron multipliers."

CHAPTER 5.

Fundamental Characteristics : Characteristic Curves for Diodes : For Triodes : Inter-Electrode Capacities : Input Impedance.

We are now in a position to discuss what are known as the *characteristics* of a valve, every valve exhibiting characteristics peculiar to its design and the voltages impressed on its electrodes. The simplest diode, as we have seen, has its characteristic of internal resistance, or anode impedance, which for a gas-free valve depends on the way in which the electrodes are designed and the anode-cathode voltage. Fig. 15 shows a typical anode voltage—anode current curve for a diode.

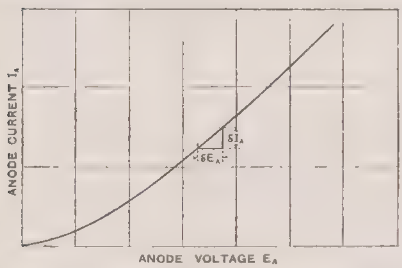


Fig. 15.—Typical relationship between anode current and anode voltage in a diode

$$\frac{\delta E_A}{\delta I_A} = R_A$$

(*anode impedance or internal resistance*).

The internal resistance R_A, as we have seen in chapter 3, is given by the ratio of the change in anode voltage to the resulting change in anode current, or $\frac{\delta E_A}{\delta I_A}$, where δE_A and δI_A represent very small changes in anode voltage and current (in amperes) respectively. It will also be recalled that due to non-linearity of the curve, the internal resistance is not equivalent to a pure D.C. resistance.

We might now reverse the line of reasoning, and instead of considering the internal *resistance*, or opposition, to electron current, visualise the inverse of opposition, and relate the *assisting* factors to electron current. The inverse of resistance is *conductance*, and so the internal conductance of the valve is $\frac{1}{R_A}$.

Characteristics of triode valve.

With this simple relationship in mind we can pass from the diode to the triode, which introduces a *controlling* factor into the picture. Due to the presence of the grid, the electron stream is modified, and the internal conductance of the valve is altered by a certain constant factor. This factor, which really defines the controlling effect of the grid, is given the abbreviation " m," or sometimes " μ."

As " m " has a definite bearing (though one which is not directly proportional for all values of grid voltage) on the performance of a valve as an amplifier, it is commonly called the *amplification factor* or, more properly, the *voltage amplification factor*.

The amplification factor is defined as the ratio of a small change in anode voltage to the change in grid voltage which is necessary to produce the same change in anode current. Expressed mathematically,

$$\text{Amplification factor m} = \frac{\delta E_A}{\delta E_G} \text{ to produce } \delta I_A \text{ (}\delta\text{ indicates a very small change).}$$

By the introduction of " m," the conductance of a triode valve is no longer $\frac{1}{R_A}$, this being modified by " m," the resultant anode current being now controlled to the extent of " m " by the grid voltage.

The internal conductance now becomes the *mutual conductance*,* sometimes called " g ", which may be expressed by the relation :—

$$\text{Mutual conductance g} = \frac{1}{R_A} \times \text{m} = \frac{\text{m}}{R_A}.$$

*Also referred to as " transconductance."

The change in anode current in receiving valves is usually of the order of thousandths of an ampere (milliamperes), and thus the mutual conductance is expressed in terms of " milliamperes of anode current per grid volt " or, briefly, " milliamps/volt."

We can now find another relation between our three characteristics, internal resistance (R_A), amplification factor (m) and mutual conductance (g). Since

$$m = \frac{\delta E_A}{\delta E_G} \text{ and } R_A = \frac{\delta E_A}{\delta I_A}$$

$$\text{then } g = \frac{m}{R_A} = \frac{\delta E_A}{\delta E_G} \times \frac{\delta I_A}{\delta E_A} = \frac{\delta I_A}{\delta E_G}.$$

In other words, the mutual conductance is obtained from the ratio of a small change in anode current to the small change in grid voltage which produces it, the anode voltage remaining constant. This is illustrated by the grid voltage—anode current curve of Fig. 16. We shall see later, when applying valves to amplifying circuits, that the characteristic of mutual conductance is of great importance, and may be taken to represent the " figure of merit " for a valve. The mutual conductance has therefore a large bearing on the efficiency of a valve, the *overall efficiency* being dependent on this factor together with the power expended in obtaining the cathode emission.

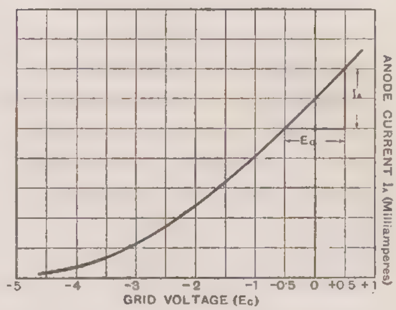


Fig. 16.—Slope of I_A–E_G characteristic is represented by

$$\frac{\delta I_A}{\delta E_G}$$

if δE_G = 1 volt, then $\frac{\delta I_A}{\delta E_G}$ = mutual conductance in mA per volt.

(*This relationship assumes linearity of the curve at points of measurement. In certain cases it is necessary to make δE_G less than 1 volt and equate to unity grid voltage*).

$$\text{Thus, overall efficiency} = \frac{m}{R_A \times W_F},$$

where W_F = filament watts.

In an effort to improve the efficiency of a valve by an increase in its mutual conductance, the value of the internal resistance may be decreased by reducing the physical distance between the anode and the cathode, which increases the effect of the positive electrostatic field from the anode on the negative space charge. But it is found that in order to keep the " m " to a reasonably high figure the anode-grid distance should be large, and this may result in bringing the grid very close to the cathode. The disadvantages of this are manifold ; apart from obvious mechanical difficulties caused by providing the small clearance without danger of contact, either when the valve is cold, or when the filament expands on heating, and in the maintenance of close consistency in manufacture, there are the dangers of grid emission to be avoided. All this involves special care in the manufacture of high mutual conductance valves.

We have seen how a positive grid current may be formed by deliberately allowing the grid to assume a positive voltage. *Negative grid current* can be due to any of three main causes :

(1) Positive-ion current produced as the result of bombardment of residual gas molecules by the electron emission.
(2) Leakage across the electrode insulating material.
(3) Electron current from the grid (grid emission).

In the case of a valve containing a trace of gas, the ion current in the grid circuit will show a reverse grid current (Fig. 17), and owing to the sensitivity of the negative grid current to small traces of residual gas, it is convenient to use direct measurement of this effect in testing valves for degree of vacuum. In normal "hard" valves the maximum negative grid current may vary from about 10^{-8} to 5×10^{-6} ampere.

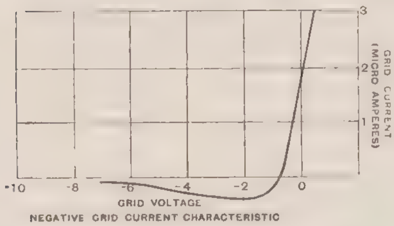


Fig. 17.—Negative grid current characteristics.

Characteristic curves.

In studying the characteristics of a valve to determine its suitability for any given application, it is useful to have reference to what we know as the *characteristic curves.* Such curves for a diode are usually of the following types :—

(1) Filament voltage (E_F) plotted against anode current (I_A), i.e. saturated space current.

(2) Emission (I_e) plotted against anode voltage (E_A), for given values of filament voltage (E_F).

(3) With A.C. applied to the anode, the R.M.S.* A.C. voltage plotted against D.C. voltage output for different values of load currents, or alternatively the D.C. output voltage plotted against rectified current for different values of applied A.C. (R.M.S.) voltage.

The third sets of curves are usually taken in conjunction with a filter circuit in which (if a condenser filter is employed) an appreciable difference in output voltage is obtained for different condenser values.

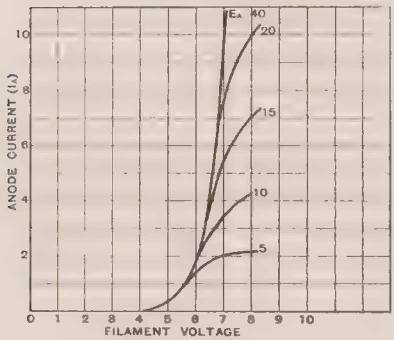


Fig. 18.—Variation of anode current with filament voltage for a bright emitter.

Examples of such diode characteristic curves are given in Figs. 18, 19 and 20. Fig. 18 is useful in the case of "clean" tungsten bright emitter filaments where the total emission is often a critical function of the temperature and thus of the applied filament voltage. It is not normally applicable to oxide-coated cathode valves. Fig. 19 enables the internal resistance of the diode to be calculated from the "slope" of the I_A–E_A curve at any point. This curve is not quite linear, but becomes more linear as the anode voltage is increased up to the point either of emission saturation or ionisation.

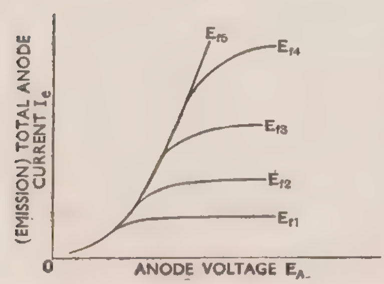


Fig. 19.—Total emission plotted against anode voltage for a typical valve.

Fig. 20 determines the value of A.C. voltage which would be required to produce any given D.C. output voltage at various load currents, or gives an estimate of the D.C. output voltage which would result from any given load current for various values of applied A.C. voltage.

*R.M.S. (Root Mean Square) = 0.707 × Peak value of alternating current (*see Appendix* 1).

Various other forms of curve are published by individual manufacturers for circuit conditions relating to different applications, such as in the case of a diode used for demodulation of radio frequency; in this case the demodulated (audio frequency) voltage may be plotted against the modulated radio frequency voltage for a given percentage of modulation and load resistance (Fig. 21).

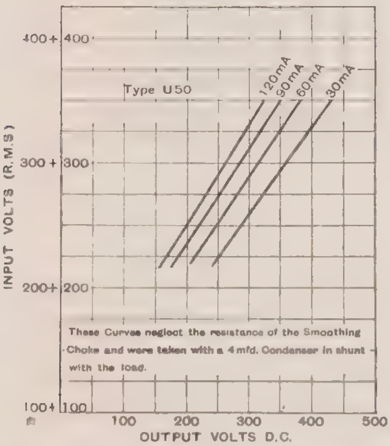


Fig. 20.—Typical characteristic for double diode as biphase half-wave rectifier with smoothing of rectified current. Relation of output (rectified) D.C. voltage to input (R.M.S.) A.C. voltage for various values of load currents.

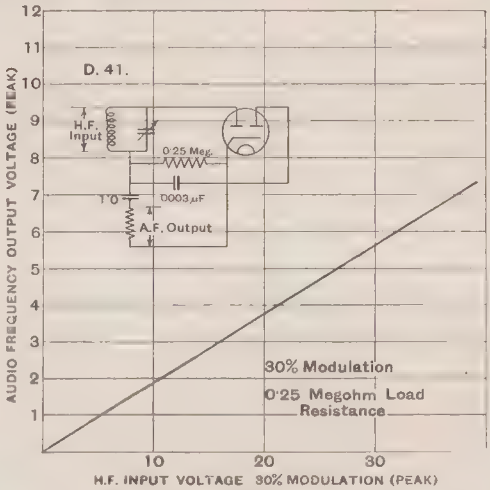


Fig. 21.—Typical characteristic of diode employed for demodulation of radio frequency. The audio frequency output voltage is related to the modulated H.F. voltage for a given percentage modulation and load resistance.

In the case of a triode, typical characteristics are :—

(1) Anode current I_A plotted against grid voltage E_G, for various values of anode voltage E_A.

(2) Anode current I_A plotted against anode voltage E_A, for various values of grid voltage E_G.

(3) Grid current I_G plotted against grid voltage E_G, for values of anode voltage E_A.

Such curves as above are taken with D.C. applied voltages and are referred to as *static* characteristics; they have a universal application and are those normally published by the manufacturer. Other curves are often available, taken under conditions of A.C. voltage applied to the grid and with a given associated circuit, and are then referred to as *dynamic* characteristics.

A point which may in certain cases assume importance is that, for valves in which the cathode is a filament carrying a D.C. heating current, all voltages normally refer to the *negative end of the filament*. In all such curves it is assumed that the anode current is " space charge limited," that is, that I_A is independent of increase in cathode temperature.

In Figs. 22 and 23 are shown curves for two typical triodes, relating *the change in grid voltage to change in anode current* for various values of anode voltage. At no point in the characteristic is the relation between anode current and grid voltage completely linear, although for a region, drawn to normal scale, it appears so. This portion, in which the anode current change is most nearly a linear function of the grid voltage change, is often loosely referred to as the " straight part of the characteristic."

The extent to which the grid voltage may be allowed to vary without causing serious non-linearity in the shape of this curve is largely dependent on the voltage amplification factor, or " m " value, of the valve. An important point to remember, however, is that, although triodes may vary considerably in design, the fundamental character of the curve shape remains the same, variations in size, shape and spacing of the electrodes merely controlling the scale of the various voltage and current relationships.

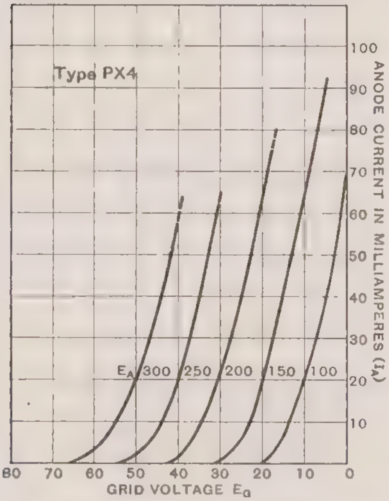


Fig. 22.—Family of curves for typical triode, relating anode current I_A *to grid voltage* E_G *for various anode voltages, in triode of low m factor.*

Characteristics from the curves.

From the anode current—grid voltage curve we can readily obtain the mutual conductance of a triode valve for, as has been seen, this is represented by the ratio of anode current change to grid voltage change. Owing to the non-linearity of the curve it is necessary to consider a very small grid voltage change only, and measure the corresponding anode current change.

g (mutual conductance) in milliamperes per volt $= \dfrac{\delta I_A \text{ (mA)}}{\delta E_G}$, where δI_A is a small change in anode current, and δE_G is the corresponding change in grid voltage, taken from the curve.

Example : In a given triode, at $E_A = 100$, the change in anode current δI_A for a change in grid voltage of from 0 to -0.5 volt is 7.3 to 4.3 = 3.0 mA.

Mutual Conductance $= \dfrac{3.0}{0.5} = 6.0$ mA per volt (at the conditions of measurement).

The mutual conductance is thus governed by the " slope " of the I_A–E_G characteristic, and for this reason is often referred to as *slope.* It will be observed that the slope decreases for a given valve as the anode voltage is reduced and the negative grid voltage is increased. From the curves of Fig. 23, $\dfrac{AB}{BC}$ determines the " slope."

The internal resistance R_A may also be arrived at for a given anode and grid voltage by examining the change in anode current resulting from two adjacent curves representing a small change in anode voltage at a fixed grid voltage. Thus :

$$R_A \text{ (ohms)} = \frac{\delta E_A \text{ (volts)}}{\delta I_A \text{ (amperes)}} \text{ or } \frac{\delta E_A \times 1000}{\delta I_A \text{(milliamperes)}}.$$

Example : In a given triode, at $E_G = 0$, the change in anode current δI_A for a change in anode voltage δE_A from 60 to 100 volts (40 V) is 4.3 to 7.3 = 3.0 mA, and the internal resistance is thus $\dfrac{40 \times 1000}{3} = 13{,}300$ ohms approx. (at the conditions of measurement).

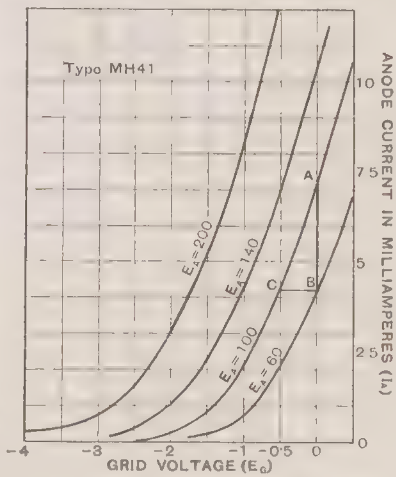


Fig. 23.—Curves for triode of high m factor.

The internal resistance increases as the anode voltage is reduced, and as the negative grid voltage is increased. From the curves of Fig. 23, it will be noted that the vertical distance AB determines this for a certain change in anode volts.

The voltage amplification factor " m " may be determined in like manner by observing the relative changes in anode and grid voltages on adjacent curves, each to produce an equivalent small change in anode current. Thus :

$$m = \frac{\delta E_A}{\delta E_G} \text{ for a fixed small change in } I_A.$$

Example : In a given triode a change in anode current δI_A of 3.0 mA is obtained equally by an anode voltage change of 60 to 100 volts with $E_G = 0$, or by grid voltage change of 0 to -0.5 volts with $E_G = 100$, and therefore

$$m = \frac{40}{0.5} = 80 \text{ (at the conditions of measurement).}$$

The change in " m " for different applied anode and grid voltages depends on the design of the electrode system. From the curves in Fig. 23, BC determines the " m " for given values of anode and grid volts. Either R_A or " m " may also be determined by simple calculation if we know " g " and one or other of the remaining constants, by application of the expression already arrived at :

$$g = \frac{m}{R_A}$$

In Figs. 24(a) and 24(b) are shown a family of curves for two typical triodes,

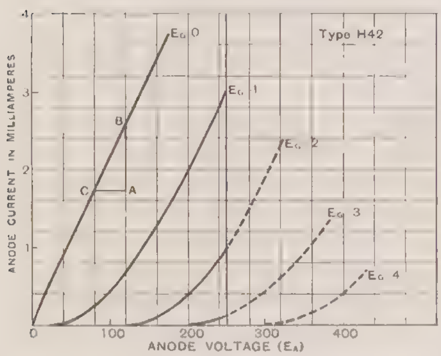


Fig. 24(a).—Typical triode of high internal resistance.

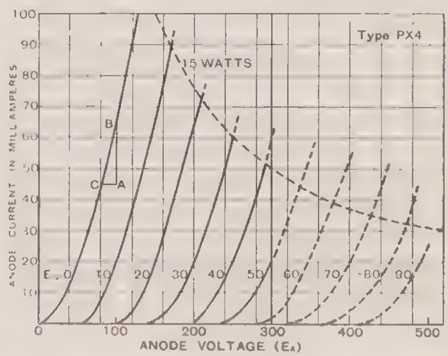


Fig. 24(b).—Typical triode of low internal resistance. Note the difference in scale.

relating the *change in anode current to the change in anode voltage* for various values of fixed grid voltages. It is seen that, although not completely linear, the curves are more nearly parallel at the lower grid voltages, but as the grid voltage is increased the " slope " of each successive I_A–E_A curve becomes successively less, the extent of which is a matter of scale and is dependent on size, shape and spacings of the electrodes, as before.

In this relationship the " slope " of an individual I_A–E_A curve is a measure of the internal resistance of the triode at any given value of anode voltage and current. Thus, as before, for a small portion of the curve :

$$R_A \text{ (ohms)} = \frac{\delta E_A \times 1{,}000}{\delta I_A \text{ (milliamperes)}}$$

From the curves of Figs. 24(a) and 24(b), $\frac{AC}{AB}$ determines the internal resistance.

Examples :

$$\text{Fig. 24(a)} \quad R_A = \frac{AC}{AB \times 10^{-3}} = \frac{40 \times 1{,}000}{0.9}$$
$$= 44{,}000 \text{ ohms approx.}$$
$$\text{Fig. 24(b)} \quad R_A = \frac{AC}{AB \times 10^{-3}} = \frac{20 \times 1{,}000}{23}$$
$$= 870 \text{ ohms approx.}$$

It will be observed that the internal resistance increases for a given valve—indicated by a " fanning out " of the curves—as the negative grid voltage increases, and also as the anode voltage (for a given grid voltage) is reduced.

In the same way as before, the mutual conductance g and the " m " value at any point may be arrived at by correlating small changes in current and voltage. From the curves of Figs. 24(a) and 24(b), AB determines the mutual conductance for a given change in grid volts.

Example :

Fig. 24(b) at $E_A = 100$ volts

the change in anode current between $E_G = 0$ and $E_G = -10$

$= 48$ mA for 10 volts

and $g = 4.8$ mA per volt

In Fig. 25 are shown typical curves relating *the change in positive grid current to change in grid voltage* in a triode. The grid current shows a steep rise upon the grid voltage becoming positive, the actual point at which grid current commences varying with different valves. Factors, other than mechanical ones, affect this point. With some cathodes, grid current may not commence until an excess of

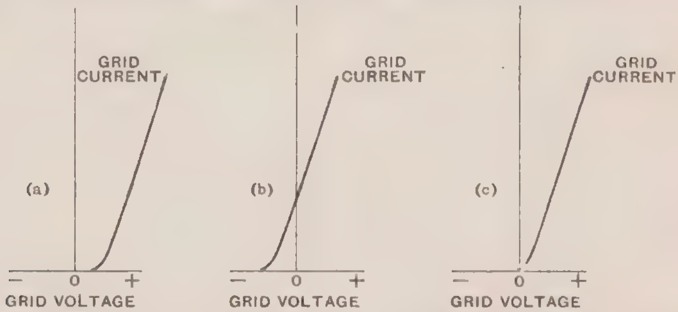


Fig. 25.—Effect of " contact potential " on starting point of positive grid current.

(*a*) *A positive grid voltage is required to overcome contact potential before grid current can flow.*

(*b*) *Grid surface more electro-positive than cathode. Condition obtaining with large cathode surface area and deposition of active material on grid—such as in indirectly heated cathode valve.*

(*c*) *Zero contact potential.*

+1 volt is applied to the grid ; in others an appreciable current flows at zero grid voltage. A realisation of the grid current characteristics, both positive and negative in direction, is of great value in assessing the suitability of any given valve for a particular application, a knowledge of the degree and point of commencement of positive grid current often being necessary.

Inter-electrode capacity and leakage.

Other characteristics which often affect the use of valves are *inter-electrode capacity* and *inter-electrode insulation* (*leakage*). As a valve is normally used in A.C. circuits, both the inductance and capacity of the various parts within and

associated with the valve often become of importance—more particularly if the applied alternating voltages are of very high frequency, as is usually the case in radio applications. It is therefore obvious that, particularly for the higher frequencies, the values of capacity between electrodes must be known, and in many cases the inductance of the electrode lead wires also enters into the picture, particularly in the ultra-high frequency range.

Each electrode in a valve has electrical capacity in relation to every other electrode. In a triode the three capacities which must be known are :—

Grid-cathode capacity : the *input capacity.*

Anode-cathode capacity : the *output capacity.*

Grid-anode capacity : the *leakage capacity.*

At high frequencies the capacities between electrodes offer additional paths in which current may flow, and this alters the theorectical considerations of behaviour as expected from the static characteristics of the valve.

The D.C. resistance between electrodes, commonly termed " insulation resistance " or " leakage," is a factor which cannot be ignored ; we have already seen that this leakage is a cause of negative grid current. The glass " pinch " used to support the electrodes is a prevalent source of leakage, and in practice special precautions are often taken in manufacture to roughen the glass surface and so increase the leakage path.

Owing to the leakage paths formed, or as the result of high dielectric losses in insulating substances between electrodes, all the inter-electrode capacities must be considered as being shunted by a resistance of greater or less value, and so when in circuit, the valve may be represented as a complicated impedance network across the grid-cathode path. This is termed the *input impedance*, and consists of the grid-cathode capacity and insulation resistance which are effectively in parallel with the input circuit to the valve. In a similar manner we may " look back " into the valve from the anode circuit, and from the anode load point of view the output impedance—consisting of the anode-cathode capacity and insulation resistance—is in parallel with the anode load.

The third capacity, namely that between the grid and anode, is known as the " leakage capacity " because it provides a leakage path for energy to be transferred from the anode to the grid circuit, or vice versa. If energy flows from the output into the grid circuit, " feed-back " is said to take place, feed-back being either positive or negative in phase. The grid-anode capacity therefore serves as a coupling between the input and output circuits, and in practice this coupling is always present, though it can be reduced or adjusted by the disposition and size of the electrodes, their supports, and their lead wires, or by introduction of electrostatic screening. This last will be considered in full later, under the head of " Screened-grid valves."

From the above considerations therefore, we see that the total effective input impedance offered by the valve to its input circuit is a function of :

(1) The input capacity—grid to cathode.

(2) The extent of feed-back—influenced by the grid to anode capacity.

(3) The insulation resistance—due to leakage across insulators.

(4) The positive-ion current—influenced by the extent of the vacuum.

(5) Grid emission—due to the nature or heating of the grid.

If the input circuit is designed with a high impedance, the necessity for high valve input impedance becomes of increasing importance, in order to avoid excessive damping due to its shunt effect across this circuit. Circuits having

an impedance of 0.5 megohm at 1000–1500 kilocycles/sec. are common, and in order that the valve shall not seriously load such a circuit, its input impedance must exceed 3 megohms.

Specialised valves, such as a type known as the Electrometer triode, have been designed to replace electrostatic measuring instruments. In such, extremely high insulation resistance between grid and other electrodes and very small residual grid currents are achieved, so that an input impedance exceeding 100 megohms at 1200 kc/sec. has been measured.

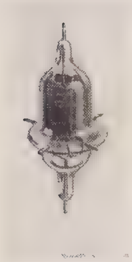


Fig. 26. The "Acorn" valve.

For ultra-high frequency radio applications, an example of a design (the "Acorn" valve) is shown in Fig. 26. In this, reduction in physical size of the electrodes and their lead wires is taken to extreme lengths to minimise capacity and inductance. Owing, however, to the exceedingly small physical size of the electrode system, assembly methods involved in large scale manufacture of this class of valve are impracticable, and so other types of valves for the ultra-high frequency range, such as that illustrated in Fig. 57(b), are tending to replace the Acorn in practice.

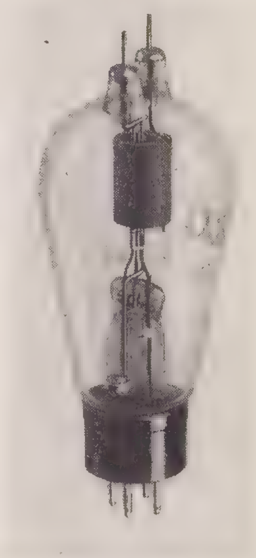


Fig. 27.—A power triode for short-wave transmitter circuits—Type DET12.

Fig. 27 illustrates a power triode for use as a radio transmitter or oscillator. In order to ensure low inter-electrode capacities and minimum lead inductance the anode and grid are supported from the glass bulb by individual leads which are brought out through the top of the bulb.

CHAPTER 6

The Indirectly Heated or Equipotential Cathode : "Noise" in a Valve : Microphony.

Hitherto we have associated the term "cathode" of a valve with a source of electron emission, in which the increase in temperature necessary to provide this emission is obtained by passing a steady heating current through it. With a filamentary cathode consisting of a long thin wire, however, the electron emission is noticeably affected by temperature changes such as would result from a heating current which is constantly changing in value, and this unevenness would cause a modulation or variation of the anode current.

A typical instance of the effect is when the filamentary cathode is heated by alternating current. Then the periodic change in direction of the current causes a subsequent periodic cooling of the filament, so that a modulation of the anode current at a frequency twice that of the A.C. supply is produced—twice the frequency because the A.C. passes through a region of zero current twice in each complete cycle. Thus, on a 50 cycle A.C. supply, a modulation of 100 cycles per second may be superimposed on the anode current which, in amplifier circuits, appears as "A.C. hum."

When, therefore, the cathode is to be heated by other than a source of steady current, it is desirable that it should be so designed that its temperature is

maintained as constant as possible despite fluctuations in the heating current. There are essentially two methods of achieving this :

(1) By the use of a heavy current, low voltage, directly heated filament.

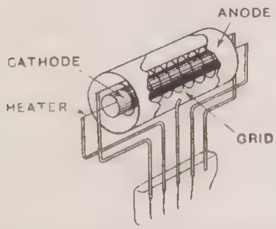
(2) By the use of an *indirectly heated cathode*, sometimes called an *equipotential cathode*.

In the case of a heavy current, low voltage filament, the thermal inertia serves to " smooth out " any sharp fluctuations of temperature, and this method may be employed with success on valves in which a small residual " hum " or ripple is not objectionable in practice. The heavy current, low voltage filamentary cathode may be successfully applied to reduce flicker due to temperature changes, but at the same time the effect of the heavy alternating current through the filament produces a strong magnetic field. This limits the use of this type of cathode as a means of reducing the emission fluctuations resulting from temperature variations caused by A.C. heating.

The indirectly heated cathode.

An indirectly heated cathode is one in which the electron emitter itself (the cathode) is separated from the source of heat, which is a filament or heater. Radiation or conduction from the heater causes the cathode to be heated indirectly. The term " equipotential cathode " is sometimes used for this arrangement, since there is no potential gradient along the length of the cathode as there would be if it was itself carrying the heating current.

In indirectly heated valves the cathode is usually made in the form of a cylinder of nickel or nickel alloy, coated on the outside with an emitting oxide, and enclosing



Early type with vacuum insulation between heater and cathode.

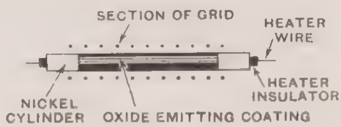


Fig. 28.—Simple indirectly heated cathode structures.

a filament which carries the heating current (Fig. 28). To distinguish from directly heated cathodes in which the filament is also the emitter, the actual filament element in indirectly heated valves is usually referred to as the *heater*, its sole function being to raise the temperature of the cathode.

Problems of design.

The time taken for an indirectly heated cathode to attain sufficient temperature for its full emission will vary with different designs, but it is in any case appreciable when compared with a normal directly heated filament, and such time must be allowed for when employing apparatus which uses indirectly heated valves.

Early indirectly heated cathodes derived their heat by radiation through vacuum from the heater, but such a system employing vacuum insulation is inefficient by reason of the large power required in the heater to radiate sufficient heat. Thus subsequent methods employed commercially make use of various forms of solid insulating material between heater and cathode, the cathode being heated mainly by radiation, but now assisted by conduction at any point of contact. It is usual for the heater itself to be sprayed with a suitable insulating material. Such a

coating of insulating material forms a smooth shell around the heater, and this shell is subjected to considerable stresses as the heater expands and contracts inside it due to the application or removal of the heater current. To avoid this difficulty it is desirable to allow for expansion without fracture of the insulator, and a method used in practice is that of making the heater as long as possible, and thus reducing the operating temperature for a given voltage. This minimises the stress on the heater insulator by the reduction of extremes of temperature variation, and it may be accomplished by making use of a heater with a double helical formation, or by folding the heater, both of which enable a greater length to be contained within a given cathode size (Fig. 29).

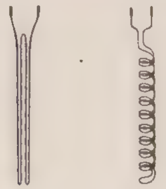


Fig. 29.
Folded Heater. *Double Helical Spiral.*

Emission from the heater to the grid and anode must be prevented by shielding, and emission from heater to cathode, if it occurs, may be prevented by operating the cathode at a negative potential with respect to the heater. In cases where large A.C. voltages exist between heater and cathode, such as where a number of valves are joined with heaters in series on an A.C. supply, the voltage between heater and cathode may be several times as great as the voltage across one heater, and shielding of the heater becomes of increased importance. In such cases, also, the grid lead should be located as far as possible away from the heater.

Reduction of "hum."

When heaters are wired in parallel on an A.C. supply, "earthing" of the heater system is best effected by returning the cathode to the centre point of the heater supply, and then the main source of "hum" is magnetic in origin. The degree of "hum" introduced in the anode circuit is shown in Fig. 30 for typical triodes and forms of heater construction. Curve A is for a straight "hairpin" type heater rated at 4 volts 1 amp; curve B for a spiral, or "reverse helix" type heater at a similar rating, and curve C also for a spiral heater, but rated at 13 volts 0.3 amp. In this last case the magnetic hum at the centre position is reduced by low heater current, and a steep rise at the ends (where the heater-cathode potential is practically zero) has been reduced both by locating the grid connection at the end of the valve remote from the heater, and by the introduction of heater shields.

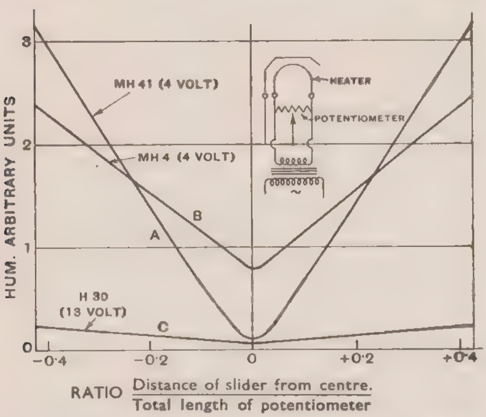


Fig. 30.—*Effect on hum of various heater-cathode designs.*

Effect on valve characteristics.

At this stage it is interesting to note the relative effects on valve characteristics of directly and indirectly heated cathodes. The basic characteristics of mutual conductance, and "m," are dependent on the relative distance between electrodes, and in order to secure a high mutual conductance $\left(\frac{m}{R_A}\right)$, without reduction in "m,"

a close grid-cathode clearance is called for. If in addition we take into consideration R_A, the internal resistance, the total cathode area available for emission is also of importance in attaining a high mutual conductance. With filamentary cathodes practical considerations set a limit both on grid-cathode clearance, and on total emitting area; on the former by mechanical difficulties in prevention of actual contact, and on the latter by the extreme length of filament required, particularly if the permissible wire thickness is limited, as is frequently the case, by restricted current consumption. A long thin filament introduces a complex mounting structure and brings other practical difficulties in its train. (It is necessary to bear in mind, however, that constant improvement in technique is occurring, with modifications in manufacturing methods.)

The use of a cylindrical cathode with its more rigid structure enables the indirectly heated system to offer advantages in the directions both of closer grid-cathode clearance and of large emissive area. In such a system the cathode diameter more nearly approaches that of the grid than if the cathode consisted of a thin wire; thus it is easier to achieve high mutual conductance in indirectly heated valves, although, owing to the greater heater wattage called for by relative inefficiency of indirect heating, the *overall* efficiency is no higher than in the filament type. The close grid-cathode clearance thus made possible brings difficulties in other directions, such as susceptibility to grid emission by direct heating of the grid, and risk of excessive variations in characteristics between individual valves of a common type.

Again, with very open grids and close grid-cathode clearance, comparatively large areas are present in which the influence exerted by the grid has little or no effect on the space charge current, and an anode current can flow which is largely uncontrolled by the grid voltage. This lack of control may become a serious limitation to high mutual conductances coupled with low " m " values. It may be minimised by constructing the grid in such a way that it produces the same " m " value but avoids an open pitch with wide " gaps "—such as by winding with many turns of fine wire rather than with few turns of thick wire. A comparison between two directly heated triodes of similar " m " value, with grids consisting of a few turns of heavy gauge wire and more turns of fine wire respectively, is shown in Fig. 31, in which the lack of control at high grid voltages in the former case is clearly indicated. The effect is intensified with indirectly heated valves owing to the large diameter of the emitting surface, and this explains why it is usual for very low resistance, high mutual conductance triodes to be of the directly heated class.

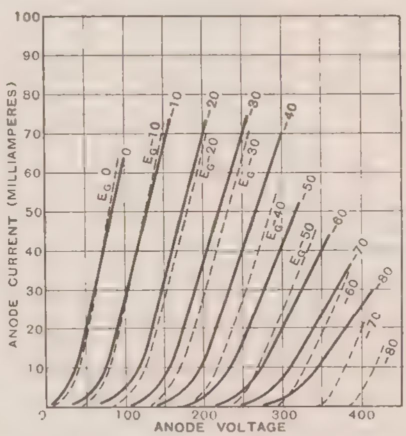


Fig. 31.—Characteristics of output (directly heated) triodes having grids wound with coarse and fine wires. Full line curves—coarse grid wires. Dotted line curves—fine grid wires.

" Noise " in valves.

In any thermionic emitter it has been found that the electron current, consisting as it does of electrons in motion, may be likened more accurately to a hail of shot rather than a stream of continuous fluid, so that the arrival of each electron at the anode is a perfectly random event. This results in minute disturbances being set up in the anode circuit, and is known as the *shot effect*. In many cases

disturbances of this nature prove a very effective limitation to certain practical applications.

The reduction of valve noise is a consideration of first importance in the design of many types of valve, and it has been proved that valve noise is at its minimum if the valve be designed and operated under conditions which make the factor $\frac{g^2}{I_A}$ as large as possible, g being the mutual conductance and I_A the anode current.

Microphony.

A further effect which often introduces a difficulty is that known as *microphony*, or *microphonic noise*. This arises from the movement of the electrodes relative to one another, and the result is a slight change in the anode current, or in the operating characteristics of the valve. The trouble is most prevalent in valves having a thin wire filament, or alternatively those in which some member of the electrode system resonates at a frequency corresponding to that of part of the sound reproducing apparatus. The filament, or electrode, may be set in vibration either by a slight mechanical shock, or by direct impact of sound waves at the mutually resonant frequency.

In the case of microphony due to the filament, the effect is a transverse vibration of the filament wire, and to reduce this, insulated supports are often used which touch the filament at various points, so producing a damping action (Fig. 32).

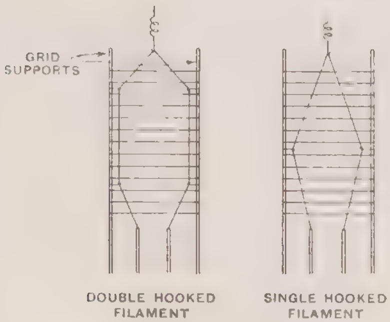


Fig. 32.—One method of damping filament wire.

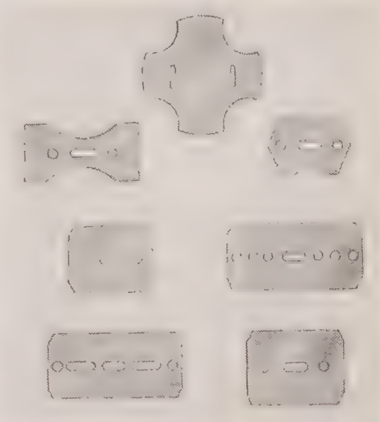


Fig. 33.—Representative mica pieces. Electrode supports pass through the holes shown.

Fig. 33.

Microphony can often be better prevented by precautions such as sprung mounting and careful location of a valve in conjunction with its associated apparatus, than by complicated internal damping systems and consequent risk of leaks.

With many small types of valves (receiving valves) rigidity in construction is obtained by anchoring the electrode supports through carefully prepared mica spacers. Consistency in characteristic and absence of noise depend upon holding the electrodes at predetermined distances from each other, which is conveniently and satisfactorily achieved by the aid of these mica spacers. Examples are shown in Fig. 33.

A dome shaped bulb is often used, in which a top support for the complete electrode system is provided by means of a suitably designed mica spacer, which holds the whole system rigidly and centrally located within the bulb.

CHAPTER 7

The Triode as an Amplifier : as a Detector : as a Generator of Oscillations : The Reacting Detector.

The application of a two electrode, or diode, valve in a rectifying circuit has been studied, and we have seen that the function of the diode for practical purposes is limited to rectification.

The main function of a triode* is that of *amplification*, which is the basis of all other applications. The property of amplification is explained by the ability of the triode to control varying degrees of power in the anode circuit (output) by means of a much smaller power expended in the grid circuit (input), and by its ability to provide power amplication the triode can also be caused to amplify voltage and current changes. In a hard vacuum valve the upper limit of the frequency at which such amplification may take place is in theory unlimited owing to the exceedingly small inertia of the electron, but in practice at high frequencies of the order of 100 megacycles per second and higher, considerations of losses due to leakage, capacity and inductance in the valve, render special conditions of design and operation necessary, and at extremely high frequencies the speed of travel of the electron itself may even be a limiting factor necessitating special valve designs.

The valve in an amplifier.

Let us consider a triode in a simple amplifying circuit (Fig. 34). A voltage E_F is applied to the filament (in this case it is also the cathode) ; a voltage E_A is applied

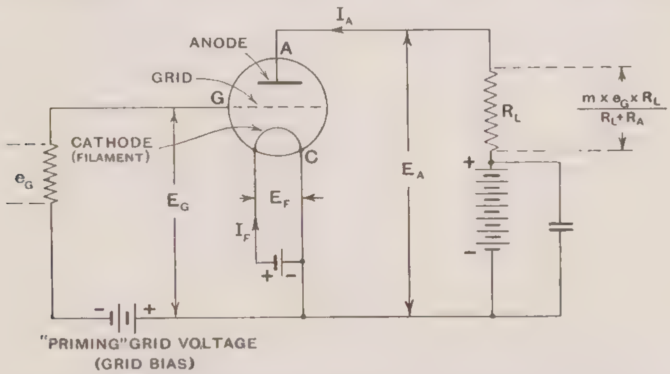


Fig. 34.—Diagrammatic representation of simple triode in circuit.

between anode and cathode, and a voltage E_G between grid and cathode. E_A is arranged to make the anode positive with respect to the cathode, and E_G makes the grid negative with respect to the cathode. Assuming the temperature of the cathode to be sufficiently high that any increase in E_F will not appreciably affect the characteristics or operation of the valve, an anode current I_A will flow in the anode circuit. We have seen that a change in E_G will cause a corresponding change in I_A and thus, if E_G is varied, a measuring milliampere meter (milliammeter) in series with the anode circuit will register such changes.

If a resistance R_L, known as the *load resistance*, is inserted in series with the anode and the H.T. supply†, such current changes take place through R_L and cause corresponding voltage changes across R_L. The A.C. voltage produced across R_L depends on the value of its resistance and upon the current changes through it, and

* Or any multiple electrode valve containing a control "grid."

† See page 12.

not directly upon the fixed voltage E_A. Thus the voltage change across R_L is a direct function of the change in the grid input voltage e_G, and the triode becomes a *voltage amplifier*.

In Fig. 34 it is seen that the grid is given a " priming " voltage to keep it at a steady negative potential with respect to the cathode. This, in valve amplifiers, is nearly always necessary, since there is a certain minimum grid voltage value (sometimes zero or slightly positive) beyond which, as the grid goes more positive, positive grid current commences to flow. Positive grid current involves the development of power in the grid circuit and is usually undesirable. This priming negative grid voltage is usually known as *negative grid bias*, the value of which varies with the characteristics of the valve, the anode voltage and the conditions of use.

It will be found that to ensure the maximum voltage amplification for a given grid voltage input and anode voltage, there is an optimum value of load resistance. This value will for a triode usually be found to be approximately twice the internal resistance of the valve, but will vary according to the departure from linearity of the anode current curves. As indicated in Fig. 34, if e_G is the input voltage to the valve, the output voltage is $\frac{m \times e_G \times R_L}{R_L + R_A}$, where m is the amplification factor of the valve, R_A the internal resistance and R_L the load resistance.

The valve as a detector.

Turning now to the use of a triode valve as a detector, we have seen (chapter 3) that all radio frequency signals consist either of a continuous wave of high frequency oscillations or of a continuous wave " modulated " by some lower or audio frequency; for intelligent reception the received signal must be demodulated to enable us to make use of the audio frequency. In radio telephony we are only concerned with " modulated " high frequency, and reference has been made to a method of " demodulating " the radio frequency wave by the rectification properties of a simple diode valve.

The high frequency wave on which modulations of audio frequency are superimposed is called the *carrier*, and in the process of demodulation, or detection, the original carrier frequency is filtered out, only the low frequency component being required for actuating the reproducing apparatus.

A *modulator* is a device which modifies the H.F. carrier current or voltage by impressing upon it a characteristic corresponding to a lower frequency than that of the carrier. A *detector*, or demodulator, performs the inverse of the modulator and, when acted upon by an alternating current or voltage which is modulated in some way, produces an effect characteristic of the modulation alone.

Anode and grid circuit detectors.

A valve may be employed as a detector in two ways—by making use of non-linearity of response either in the anode circuit or in the grid circuit. When use is made of the non-linearity of the anode current-grid voltage curve, this is known as anode circuit, or *anode bend* detection, and when use is made of the curvature of the grid current-grid voltage curve, this is known as *grid circuit* detection, which may also be called " grid leak " detection, or " leaky grid " detection.

Advantages for *anode bend detection* may be said to be:

(a) The valve offers a high input impedance, and therefore low damping on the input circuit.

(b) The valve may conveniently be arranged to accept large input voltages by suitable adjustment of anode and grid voltages—the larger the applied signal voltage, the greater the detection efficiency and the less the distortion of the modulated characteristic.

(c) Signals of high modulation percentage may be demodulated with small distortion of the low frequency waveform.

On the other hand, for very small input voltages three disadvantages occur :

(a) The detector is insenstive.

(b) The whole of the modulated carrier is applied over a markedly non-linear portion of the curve, with resultant " double-rectification " or distortion of the low frequency component.

(c) The internal impedance of the valve is highest where detection efficiency is greatest, resulting in the necessity for a high value of load resistance.

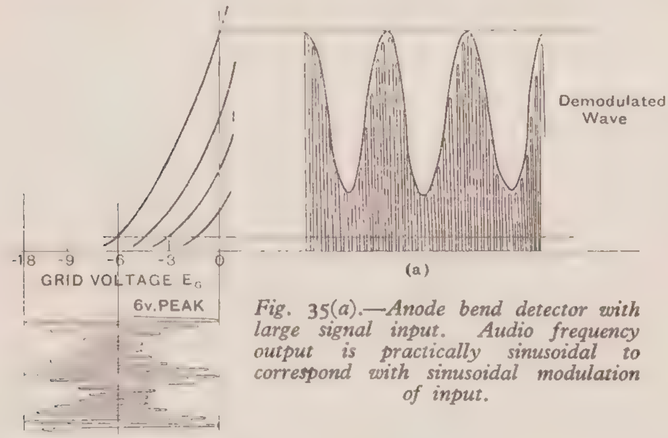


Fig. 35(*a*).—*Anode bend detector with large signal input. Audio frequency output is practically sinusoidal to correspond with sinusoidal modulation of input.*

Fig. 35(a) shows the curves for a triode suitably biased for anode bend detection, Fig. 35(b) being a magnified section of the curve to illustrate the relative curvature in the case of a very small signal. The actual bias applied is usually adjusted to the input signal.

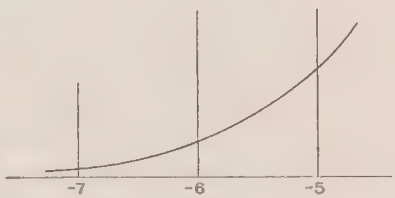


Fig. 35(*b*).—*Enlarged portion of valve curve Fig.* 35(*a*) *showing non-linearity of anode current curve with small input, giving rise to distortion (due to double rectification) of audio frequency output.*

In *grid circuit detection* the mechanism is quite different from that of anode circuit detection. In this case the signal is applied at any point where positive grid current can be caused to flow by the positive half-cycles of the modulated carrier ; in other words the grid cathode system may be viewed as a simple diode, the audio (low) frequency modulation voltage appearing across a resistance between the grid and cathode and being then amplified through the anode circuit of the valve. As it combines detection and amplification, the grid circuit detector is, in general, more sensitive than the anode bend detector.

A modulated signal may be applied to the grid through a small condenser C_1 shown in Fig. 36, the leakage resistance of this condenser

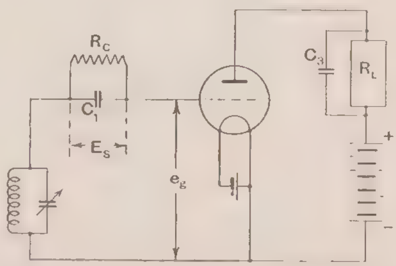
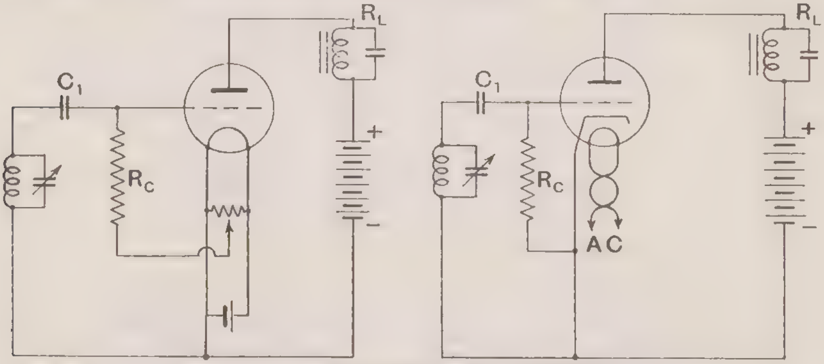


Fig. 36.—*Circuit for grid detection with grid condenser* C_1 (C_3 *is used to shunt the R.F. components in the anode load*).

being indicated by R_C. In practice this leakage is artificially increased by introducing R_C in the form of a. resistance, called the *grid leak*, either across the grid condenser or between grid and cathode. To ensure the highest sensitivity, the leak resistance should be connected such that the grid normally takes up a standing voltage (without input signal) corresponding to the exact commencement of positive grid current. In the case of filamentary cathode valves, where grid current usually starts at some slightly positive point, the grid leak may be returned to the slider of a potentiometer across the filament, and this will enable the correct voltage to be obtained, Fig. 37(a). Should positive grid current commence at some negative grid voltage, as in the case of many indirectly heated cathode valves, it is satisfactory to connect the grid leak to cathode, Fig. 37(b).



ARRANGEMENTS FOR GRID CIRCUIT DETECTION.

Fig. 37(a).—Directly heated valve, showing grid resistance joined to potentiometer across filament and adjusted to point of commencement of grid current.

Fig. 37(b).—Indirectly heated cathode valve, showing grid resistance joined to cathode, assuming grid current commences at some negative grid voltage.

Advantages of the *grid circuit* method of detection may be said to be :

(a) The detector is sensitive.

(b) With small signal input, comparative freedom from distortion may be obtained, in relation to either anode bend or simple diode detectors.

(c) The anode impedance at the point of operation is comparatively low, being in effect similar to that obtaining with the triode operating as an audio frequency amplifier, so that normal values of load resistance may be employed.

Some disadvantages of the method are :

(a) With a large signal input it is difficult to avoid the presence of anode bend detection in some degree, resulting in amplitude distortion of the rectified waveform.

(b) A compromise must be made between frequency distortion and sensitivity.

(c) The comparatively low input impedance may cause serious damping of the input circuit.

The valve as a self-oscillator.

We now come to a consideration of the valve as a *generator of oscillations.* The property of amplification possessed by the valve affords a means for the generation of alternating voltages of frequencies varying from a few cycles per minute up to many millions per second.

The condition for oscillation generation, or *regeneration*, *retro-action* or *reaction* is that some power from the output circuit of the amplifier is transferred to the

input circuit, and in order to appreciate the action it is necessary to be familiar with the principles and operation of the *tuned*, or *oscillatory circuit*.

In many circuits containing inductance and capacity, it is possible to produce a condition in which, when fed from an alternating current source, the impedance presented is a maximum at a given frequency, called the *resonant frequency*, which depends on the relative values of inductance and capacity in the circuit.

The resonant frequency is denoted by the expression :

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

where L = inductance in henries.
C = capacity in farads.

When L and C are adjusted to cause a resonant circuit to be set up at a given frequency, such a circuit is said to be *tuned* to that frequency. The frequency to which any such circuit is tuned can therefore be varied by increasing or decreasing the values of inductance and capacity it contains. Such a circuit may be connected across the grid-cathode circuit of a valve, and if an alternating voltage of the resonant frequency of the circuit is applied across it, a voltage approaching the input value will be applied to the grid. A similar tuned circuit connected in the anode circuit forms the load which, when tuned to resonance, is sufficiently high in value to enable the valve to give appreciable amplification. Thus, an amplified value of the voltage input appears across the output tuned circuit, when both input and output parallel circuits are tuned to resonance at a given frequency.

Now suppose the anode coil is electrically coupled to the grid coil ; the coupling (magnetic if inductively coupled, and electrostatic if capacity coupled) can be arranged so that the alternating voltage across the anode coil is either in phase with, or in opposition to, the alternating voltage across the grid coil. Fig. 38 shows such a circuit with inductive coupling, L_1C being the tuned grid circuit. In practice it is not necessary for the anode circuit to be tuned to resonance, the coupling between it and the grid coil, together with the amplification, resulting in sufficient voltage build-up for a state of oscillation.

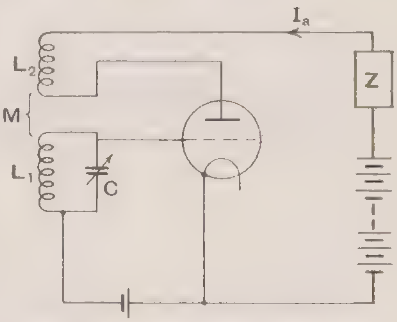


Fig. 38.—Regenerative circuit with inductive coupling.

Take the case of the voltages being " in phase." Viewed individually, both grid and anode circuits possess positive resistance which limits the voltage, but with sufficiently tight coupling some of the output voltage is added to the original input voltage, and this additional voltage is amplified by the valve and appears across the tuned output circuit. As soon as the amplification is more than sufficient to balance the losses due to resistance in the whole system, the circuits develop a negative resistance, and continuous generation of oscillations at the resonant frequency of the tuned circuit is set up. The valve is then said to be *oscillating*, the frequency of oscillation being determined by :

$$f = \frac{1}{2\pi\sqrt{LC}}$$

The time taken to build up to an oscillatory condition is practically negligible in ordinary circuits.

The general conditions for oscillation or regeneration are therefore :

(a) The valve and circuit must amplify sufficiently to overcome the losses in the system.

(b) The output must be coupled to the input in correct phase and sufficient amplitude to maintain oscillation.

Once sufficient coupling has been established to overcome the natural resistance of the circuit, the amplitude of the oscillatory voltage is limited only by the power handling capabilities of the valve.

Methods of coupling for self-oscillation.

Regeneration may be obtained by several types of coupling. First, with inductive coupling, either the grid or anode circuit may be tuned : with tuned grid,

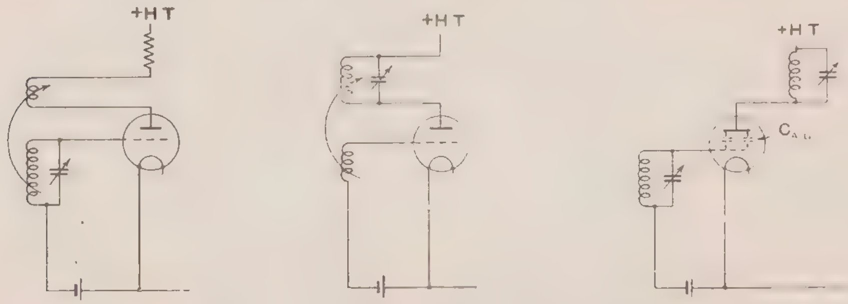


Fig. 39 (*a, b and c*).

(*a*) *Regenerative circuit with tuned grid.* (*b*) *Regenerative circuit with tuned anode.* (*c*) *Regenerative circuit with anode and grid tuned circuits coupled by grid-anode capacity.*

the circuit is as shown in Fig. 39(a). The tuned anode circuit is shown in Fig. 39(b). Secondly, the coupling between the anode and grid circuits may be entirely capacitive, as shown in Fig. 39(c). The capacity may consist of that normally existing as inter-electrode capacity between grid and anode within the valve, and that of the connections ; such capacities always exist and at high frequencies may offer a sufficiently low resistance path to effect coupling and cause self-oscillation, even though there is no mutual inductance coupling between output and input circuits.

Owing to the grid-anode capacity, the effect of tuning grid and anode circuits to resonance, even though they may be carefully shielded from each other electrically, may be to set up an oscillatory condition ; alternatively, capacity coupling external to the valve may be arranged which increases the grid-anode capacity by some additional value. In this case again, a tuned circuit may be included in either grid or anode circuit of the valve.

Many practical variations of regenerative circuits may be employed. A common one is that known as the *Hartley circuit*, forms of which are shown in Figs. 40(a) and 40(b). It will be observed that a grid condenser C_3 shunted by a

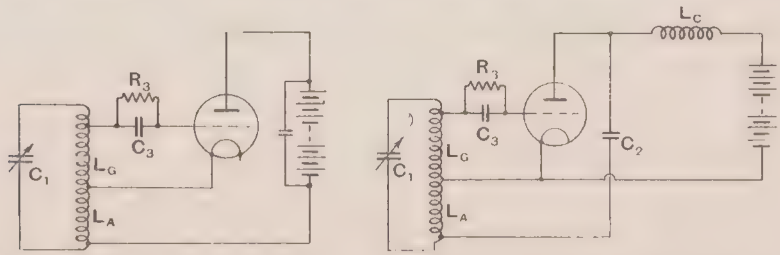


Fig. 40(*a*).—*Hartley circuit, series-feed.* *Fig.* 40(*b*).—*Hartley circuit, shunt-feed.*

resistance R_3 (the " grid leak ") is connected in the grid circuit ; an alternative would be to bias the grid by a permanent negative voltage relative to the cathode. A negative grid voltage is usually essential and always desirable to limit the power dissipated on the anode which might become excessive and cause destruction to the valve by overheating. Such a negative grid bias may be applied automatically by means of the grid condenser and leak, or by allowing the anode current to flow through a resistance in series with the cathode. The most common method is that shown, with a resistance in the grid circuit.

When the valve is in an oscillatory condition its grid is driven positive on half cycles of feed-back voltage and draws current. This grid current flows through the resistance R_3 and causes a voltage drop to appear across it, the polarity being such as to make the grid negative with respect to the cathode ; in this way the negative grid bias is obtained. In such a circuit it is essential that oscillation should be maintained so long as the anode voltage is applied to the valve. Other forms of oscillatory circuits more suitable for generating very high frequencies, are commonly used, but we have not the space to include them here.

Frequency doubling.

Since the anode current characteristics of the valve are not linear, pure " sine wave " voltage on the grid will not produce " sine wave " oscillations of anode current, but will introduce harmonics ; if the load circuit is tuned to the frequency of oscillation, these harmonics will not appear in it, but sometimes it is useful to utilise the harmonic frequencies generated, in which case the load circuit is tuned accordingly. An arrangement in which the load circuit is tuned to the second harmonic is termed a *frequency doubler*.

In cases where continuous oscillations of large amplitudes are required, as in transmission of power, it is often more economical to employ a relatively small valve for generation of low oscillatory voltages at the desired frequency, and subsequently to amplify these voltages by means of larger valves in suitable amplifying circuits. This system is sometimes known as the *power drive* method of obtaining oscillatory voltages of a high order.

The reacting detector.

Regeneration is also often employed to advantage in the *reacting detector*. Fig. 41 shows a grid circuit detector having part of its output coupled to the grid

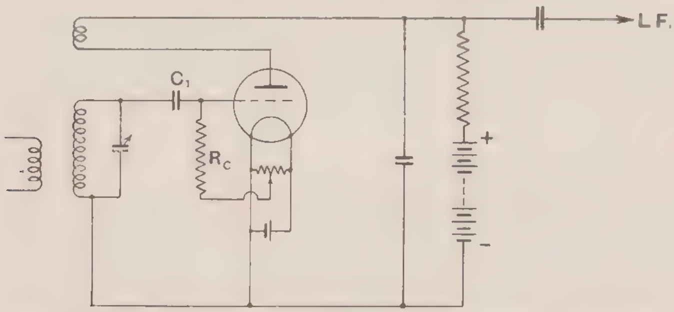


Fig. 41.—Regeneration with grid leak detector (inductive feed-back).

circuit in the correct phase to assist in regeneration. By this means the triode detector obtains a further advantage in sensitivity over the diode, in that it can be made to act as an amplifier of radio frequency in addition to an amplifier of the

low frequency modulation voltage. The reacting triode detector is therefore performing three functions within the one set of electrodes :

1. H.F. amplification.
2. Detection.
3. L.F. amplification.

Control of regeneration may be secured by a variable resistance in series with one of the coupled circuits, by varying the coupling of the grid and anode circuits electromagnetically or electrostatically, or by control of the electrode voltages.

CHAPTER 8

Types of Amplification Circuit : "Class A," "Class B," "Class C" : Distortion : Intervalve Coupling : Resistive and Inductive Loads : The Triode in a Power Amplifier.

Valve amplifiers in practice may be classified into three main groups, which for ease of reference are commonly denoted as "Class A," "Class B" and "Class C." "*Class A*" may be described as the operation of a valve in an amplifier under conditions of constant internal resistance R_A, over the entire cycle of electrical variation due to the applied signal. Thus, a condition of use is fixed by given values for E_A and I_A (or E_G), the mean values of which remain sensibly constant whether an alternating voltage e_G is applied or not.

"*Class B*" is the term applied to amplifiers in which the grid bias voltage is such that under static conditions the anode current is practically zero ; in other words, the anode current flows during approximately one half of each cycle of the input grid voltage when the signal is applied. "Class B" is sometimes subdivided into two groups : first, that in which the valve operates without being allowed to take positive-grid current, by suitable adjustment of the grid bias and the amplitude of the applied voltage, and secondly that in which the positive half-cycle of the signal voltage drives the grid voltage into the positive region and causes the grid to take current. The former group is sometimes designated "*Class AB1*." The latter group may be described as "*Positive drive Class B*," or sometimes "*Class AB2*."

"*Class C*" may be described as the operation of a valve in such a way that under static conditions the applied values for E_A and E_G in relation to the characteristics of the particular valve concerned are more than sufficient to reduce the anode current I_A to zero, so that when the input voltage e_G is applied to the grid, appreciable amplitude is required before anode current flows on the positive half-cycle. Radio frequency power amplifiers operated at high efficiency belong to this class.

Amplifier circuits : Distortion.

We have seen that for amplification of a given voltage applied between grid and cathode, (e_G), the valve requires to be fed with a source of power from an external source, and to be provided with a suitable "load" in series with its anode and that source of power. The valve acts as a source of alternating voltage which becomes equal to $m \times e_G$, and this produces an alternating current through the load R_L. If R_L is a pure resistance the voltage developed across it is independent of the frequency, and this voltage may be applied across the grid-cathode circuit of a second valve if desired, where a further voltage amplification takes place. Two or more valves so connected are said to be joined in *cascade*.

The principal aim in the design of multi-stage amplifiers is that of high amplification of the initial input voltage without *distortion* of the input waveform. Thus, in an ideal amplifier, no " waveform distortion " exists. The main types of distortion likely to be encountered in practice are :

1. *Phase distortion*, in which the phase relationship of the several components of the complex wave are altered. This is of small practical importance except in special cases.
2. *Frequency distortion*, in which equal signals at different frequencies are not equally amplified. This form of distortion is not due to the valve alone, but to the characteristics of the input and output circuits when allied to the equivalent input and output valve impedance. It becomes of importance not only in audio frequency amplifiers in which its effect is obvious, but in radio frequency amplifiers required to amplify a modulated H.F. voltage made up of many frequencies within the range of modulation.
3. *Amplitude distortion*, in which a non-linear relation exists between the output current or voltage and the input voltage. It is this non-linearity which has already been shown to be a cause of rectification when applied to the anode bend detector. Amplitude distortion leads to the introduction of frequencies in the output which are not present in the input and is normally caused by curvature over the operating portion of the valve characteristic, or by some characteristic of the output circuit. A non-linear amplifier introduces harmonics of all frequencies present in the input, together with additional components, into the resultant waveform.

Resistance and inductance-coupled amplifiers.

In multi-stage amplifiers the anode load for each valve may consist either of a pure resistance or an inductance, and similarly the input voltage to the grid of each valve may be applied across a pure resistance or an inductance. If inductances are used these may be tuned or untuned. In the simplest case, that in which both anode output and grid input voltages are applied across pure resistances, the

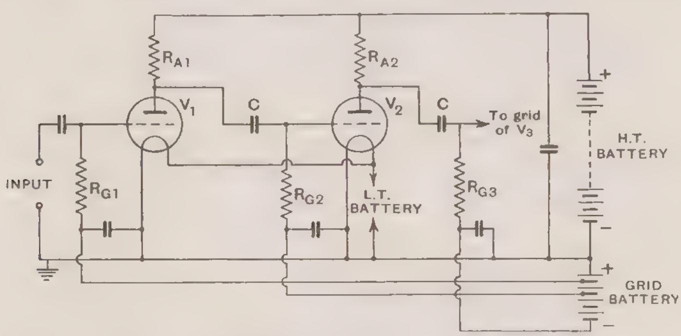


Fig. 42.—Fundamental circuit of two-stage resistance-capacity coupled amplifier. R_{A1}, R_{A2} *are anode loads.* R_{G1}, R_{G2}, R_{G3} *are grid resistances (sometimes erroneously referred to as grid leaks).*

coupling between the anode of one valve and the grid of the following valve is provided by the capacity of a condenser, and hence the term *resistance-capacity* coupling (see circuit Fig. 42) is commonly used. With the type of circuit involving inductive loads, we have to consider the variation of load impedance

with frequency, and it becomes apparent that if such a load is used in a valve amplifying circuit which is handling input voltages covering a range of frequencies, the voltage amplification becomes in general a function of the frequency. If the inductive load is " air-cored," that is, its inductance is obtained solely by the number, dimensions and disposition of the coils composing it, the high impedance necessary to result in adequate voltage amplification is only obtained by including such an inductance in a tuned circuit.

At radio frequencies the presence of capacity in the valve very much impairs the efficiency of the resistance-capacity amplifier, and the tuned amplifier, which does not suffer from this defect, is exclusively used. A further advantage of this is that the amplification is high only over a narrow band of frequencies, thus enabling selected transmissions to be received. Such an amplifier is shown in

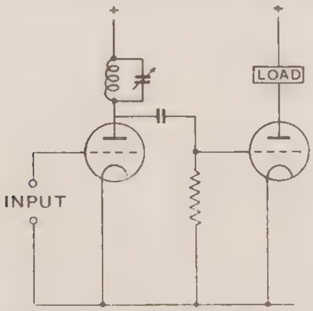


Fig. 43(a).—" Tuned anode " coupling.

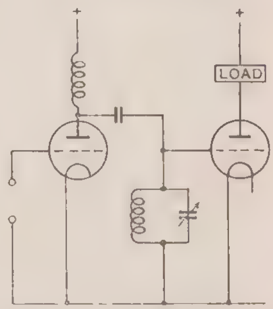


Fig. 43(b).—" Tuned grid " with aperiodic anode load.

Fig. 43(a); this is usually known as " tuned anode " coupling. A variation of the same in which the anode load is untuned and the following grid circuit tuned is shown in Fig. 43(b), and is known as " tuned grid " coupling.

In the case of transformer coupling, either iron or air cored components may be used, and either or both the windings may be tuned or untuned. Transformer coupling, unlike the forms discussed so far, is capable of enabling a voltage amplification greater than the " m " value of the associated valve to be obtained, as a step-up in voltage may be secured in the transformer itself. The most usual forms of transformer coupling are :

(1) The loosely coupled type (usually air-cored) with a tuned secondary, as used in radio frequency circuits, to amplify at a given frequency or narrow band of frequencies.

(2) The tightly coupled laminated iron-cored type, untuned to any particular frequency, and used for amplification over a band of frequencies in the audio range (say, 100–10,000 cycles/sec.).

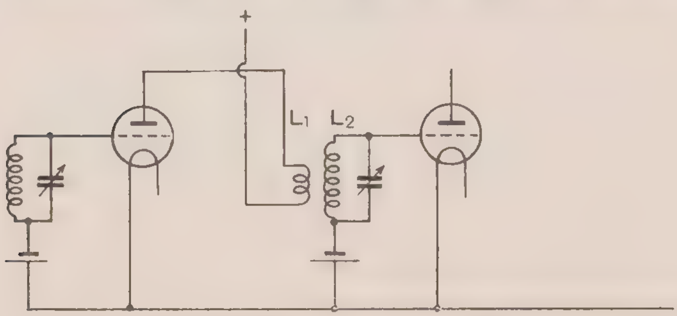


Fig. 44.—Loose coupled transformer circuit with tuned secondary.

Fig. 44 shows a typical loose coupled transformer circuit having a tuned secondary. The secondary tuning capacity is variable and in practice is adjusted to give maximum amplification ; when tuned to resonance the impedance offered by the secondary circuit is transferred by the mutual inductance of the coils to the primary winding and hence to the anode circuit. Assuming absence of instability, the percentage of maximum amplification depends on :

(1) The closeness of coupling between primary and secondary.
(2) The number of primary turns.
(3) The distributed capacities.

Amplification of high (radio) frequency voltage has many applications. In receivers for radio, there are various reasons which make it advisable to amplify the signal at radio frequency before it is detected. One is that the efficiency of any ordinary kind of detector is low at input voltages considerably less than 1 volt, whereas the voltage delivered by the average aerial may be only a few millivolts. We have already seen that in cases of a diode or anode bend detector, too small a radio frequency signal input will introduce distortion of the audio frequency rectified voltage, and hence pre-detector amplification is valuable. A second reason is that an increased number of tuned amplifier circuits will progressively increase the amplification at one given frequency in relation to that at other frequencies, or, in other words, *frequency selectivity* will be increased. Triodes of normal design are, however, very limited in their application to radio frequency amplifiers, and methods of overcoming the limitation of such valves for amplification at high frequencies will be considered later.

Audio frequency amplifiers.

We now turn to the tightly coupled iron cored transformer, not intentionally tuned, and normally associated with audio frequency amplifiers. Such transformers, owing to their distributed capacities, cannot strictly be described as untuned, as

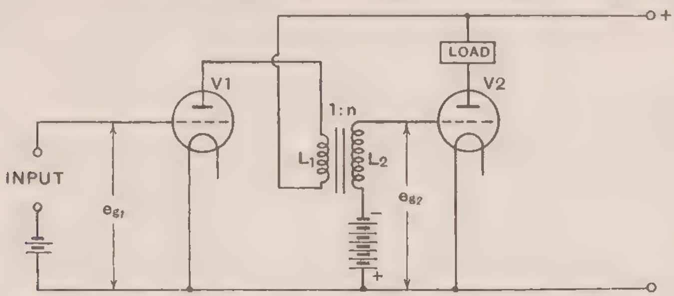


Fig. 45.—Typical transformer coupled amplifier for audio frequencies.

these capacities, together with valve capacities, have considerable effect, especially at the higher audio frequencies. Fig. 45 shows a diagram of connections for an audio frequency amplifying stage. (In this circuit the grids of V1 and V2 are biased negatively so that no grid current intentionally flows.)

The audio frequency transformer used as coupling between stages of an amplifier is necessarily an iron cored one as otherwise it is impossible to obtain sufficiently close coupling and sufficiently high impedance in the primary winding. The impedance of the primary may be increased either by using a large number of turns of wire or by improving the quality of the iron in the core. Fig. 46 shows that the impedance by no means remains constant with change of frequency. The impedance of L_1 must therefore be made much greater than the resistance R_A

of the valve V_1 at all frequencies to be amplified, making it possible to secure constancy of amplification despite wide variation in impedance.

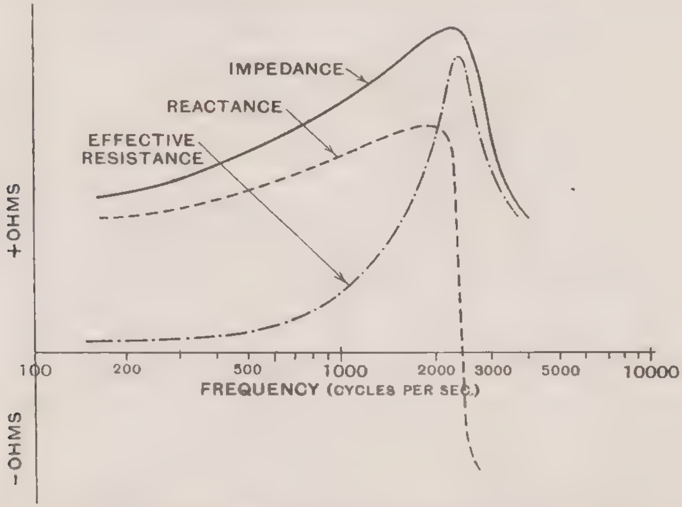


Fig. 46.—Variation of impedance, effective resistance, and reactance with frequency, in typical audio frequency transformer primary.

The effect of *leakage inductance* between primary and secondary windings is often important, this—coupled with the effects of distributed capacities—tending to set up a state of incipient instability in the amplifier. To offset such effects the secondary windings of audio transformers are often deliberately loaded with a shunt resistance which has the result of flattening any resonance peak and in

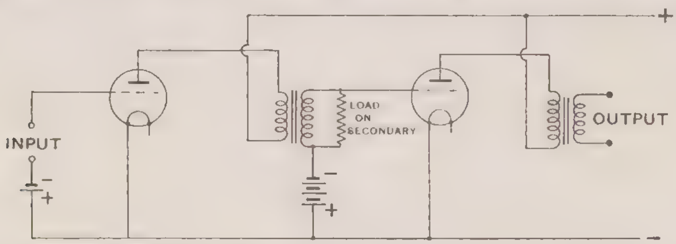


Fig. 47.—Illustrating audio frequency transformer with loaded secondary.

many cases materially improves the quality of the amplified signal. A transformer with a *loaded secondary* is shown in the circuit in Fig. 47, in which the maximum *possible* amplification is reduced but the maximum *useful* amplification may be increased.

Cases frequently arise in practice in which the transformer has to feed into a valve in which positive-grid current is permitted to flow (positive drive " Class B "). In all such cases the intervalve coupling transformer must be of entirely different character from that used for a purely voltage amplifier such as has been dealt with above ; in a transformer carrying a substantial direct current in the secondary winding it is not practicable to employ step-up ratios of a value which would otherwise be used.

Considerations of a power amplifier (radio or audio frequency).

Hitherto we have considered the application of the triode valve in an amplifier in which voltage amplification only is required ; we have now to consider the case

in which the valve is to be employed as a *power amplifier*. In general there are three main aspects affecting the design and performance of such a valve :

(1) The frequency or range of frequencies over which the valve is to operate.
(2) The expenditure of power in the grid (input) circuit.
(3) The requirement of power handling capability in the anode (output) circuit.

In the requirements of a power amplifying valve for high or " radio " frequency circuits, considerations of inter-electrode capacities and leakages become of importance in the manner already discussed in connection with voltage amplification. When the effects of the damping on tuned circuits and feed-back have been taken into account, the requirements then become dependent on points (2) and (3) above.

Normally, in conditions which avoid grid current, e.g. audio frequency, the grid of the valve is maintained at a sufficiently high standing negative potential, so that the expenditure of power in the grid circuit is negligible. (In practice, the prevention of peak grid voltages of such magnitude as would cause some grid current on the peaks, is difficult.) On the assumption that the grid current may be neglected, the expenditure of power in the grid becomes solely dependent on the frequency of the applied signal and on any leakage resistance present in the valve or wiring.

The requirement of power in the anode circuit is a matter common to all applications of the power amplifying valve, and in the design and operation of a triode for this application the following must be taken into account :

(1) The A.C. power which is required to be developed in the " load."
(2) The power lost in the form of heat generated within the valve itself.
(3) The anode voltage at which the valve is to operate.
(4) The amount of standing anode current which can be supplied from the source of D.C. power.
(5) The total cathode electron emission required.
(6) The resulting heater or filament wattage required.
(7) The A.C. grid voltage required to give the required change in anode current (i.e. the mutual conductance of the valve).
(8) The linearity or otherwise of the valve curves in the region of high grid bias. (If the power stage employs a tetrode or pentode (see chapter 9), consideration must also be given to the power lost in the screen grid, and to the curvature of the characteristic in the region of low grid bias.)

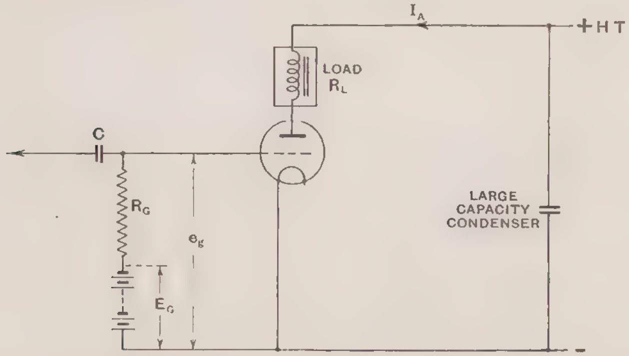


Fig. 48.—Typical circuit for power amplifying triode. R_G *may be replaced by an impedance, such as a transformer secondary winding.*

Fig. 48 shows a typical triode power amplifying circuit for L.F. or " audio " frequencies in which a source of steady current and voltage is fed to the anode via the load R_L, the grid being maintained at a sufficiently high negative potential E_G by the " grid battery " to prevent grid current flowing even on full modulation, and the A.C. signal input voltage e_g being fed to the grid across a resistance R_G via an isolating condenser C.

If the alternating component of the anode current through the load is i_a we have, for a given frequency :

$$i_a = \frac{me_g}{R_A + R_L} \quad \text{(i)}$$

where m = amplification factor and
R_A = internal resistance of the valve.

The voltage developed across the load is :

$$i_a R_L = me_g \frac{R_L}{R_A + R_L} \quad \text{(ii)}$$

Therefore the power developed in the load is given by :

$$\text{(i)} \times \text{(ii)} = \frac{m^2 e_g{}^2 R_L}{(R_A + R_L)^2} \text{ (peak)}$$

It must be borne in mind that the values for e_g and i_a are " peak " values, and if the power is required to be known as an R.M.S. value, the peak voltage and current must first be converted accordingly (peak = $\sqrt{2}$ R.M.S.).

Calculation of power output from characteristic curves.

Let us see how the power output of a triode may be derived from its characteristic curves. Fig. 49 shows a family of I_A–E_A curves for a given triode. Consider the case of an anode load in which the D.C. resistance is negligible compared with its A.C. resistance, which is normally the case with a power circuit in practice. The variations described by the anode current cycle are determined by the *load line*, and in order to ensure absence of appreciable amplitude distortion, the variations are limited by the curve for E_G = O and the horizontal line below which the characteristics have appreciable curvature.

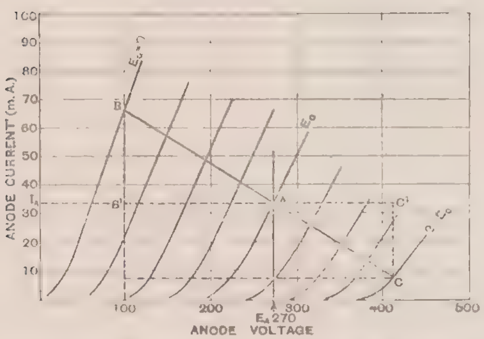


Fig. 49.—I_A–E_A *curves for triode, showing load line.*

Assuming avoidance of grid current, complete absence of amplitude distortion implies an anode current change from the average value in the positive half-cycle to an exactly equal value in the negative half-cycle. This, assuming parallel and equally spaced curves, occurs when e_g swings alternately from the fixed bias value up to the point of grid current and down to twice the bias value. This equality is seldom realised owing to the non-linearity of the characteristics, and a small percentage of amplitude distortion is usually tolerated. With triodes an introduction of the second or " even " harmonic to the extent of approximately 5% of the amplitude of the fundamental is usually accepted as a basis for estimation of power output, and this is achieved where the peak anode current increase is about 10% greater than the peak anode current decrease over a complete cycle.

A load line BC (Fig. 49) may be drawn through the point A (representing the standing anode current I_A) the slope of which satisfies this condition. B^1B represents the increase in anode current (peak), C^1C represents the decrease in anode current (peak), and B^1C^1 represents the total swing of anode voltage (peak to peak).

The resistance of the load under this condition is readily determined by Ohm's Law from the relation :

$$R_L = \frac{B^1C^1 \text{ (volts)} \times 1000}{(B^1B + C^1C)}$$

where the measures of B^1B and C^1C are in milliamperes.

When B^1B is 10% greater than C^1C, this value for R_L is the only resistance of the load which will satisfy the condition of 5% second harmonic distortion when the particular valve, E_A and I_A (or E_G) are specified.

The slope and extent of the load line determines automatically the power output which a valve can deliver into its load under the specified operating conditions. Thus :

$$\text{R.M.S. Power} = \text{R.M.S. Voltage} \times \text{R.M.S. Current}$$
$$= \frac{\text{Peak volts}}{\sqrt{2}} \times \frac{\text{Peak current}}{\sqrt{2}}$$

The total R.M.S. voltage developed across the load is half the R.M.S. voltage swing, and is represented by :

$$\frac{B^1C^1}{2\sqrt{2}}$$

Similarly the total R.M.S. current through the load is represented by :

$$\frac{B^1B + C^1C}{2\sqrt{2}}$$

Therefore the R.M.S. power developed in the load is represented by :

$$\frac{B^1C^1}{2\sqrt{2}} \times \frac{B^1B + C^1C}{2\sqrt{2}}$$

and equals :

$$\frac{\text{Total peak current swing in mA} \times 10^{-3} \times \text{Total peak voltage swing}}{8} \text{ (in watts).}$$

The curves in Fig. 50 indicate the variation in power output and second harmonic distortion with varying values of load resistance, under given conditions of anode voltage and standing anode current. For a triode, the maximum power output for a given percentage distortion is limited by :

(1) The applied anode voltage E_A.
(2) The slope of the I_A-E_A curve (internal resistance or anode impedance, R_A).
(3) The standing anode current I_A.
(4) The extent of departure from linearity of the valve curves below I_A, which affects R_L.

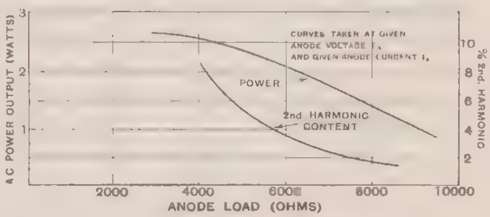


Fig. 50.—Relationship of power output and harmonic distortion in typical triode with varying values of load resistance.

Anode dissipation.

The product of the anode voltage E_A and the standing anode current I_A represent the power developed within the valve itself, and dissipated there in the form of heat. This is known as the *anode dissipation*, or anode wattage, and must not be confused

with the output wattage developed in the load. Considerations of operating anode voltage and wattage dissipation are important features in the design of a valve for power amplification. If a valve is required to deliver a large power output by virtue of high applied anode voltage, the design will also have to allow for adequate insulation between the anode and other electrodes. If a large heat dissipation at the anode is to be allowed for, it is often necessary to make the anode of a metal which has a high melting point, such as molybdenum, or sometimes of carbon, and of a wide surface area for better heat dissipation. Larger anode surfaces call for better and more complete pumping during manufacture to expel occluded gases, and the benefits of " getters " (see chapter 2) are sometimes employed, particularly in the case of smaller power valves.

In some cases the heat generated at the anode is such as to call for designs in which hard glass or silica may be employed for the envelope, or in which the envelope is entirely dispensed with so that the anode itself becomes exposed to air. Such valves are called *air-cooled anode* types, and may be cooled by natural or forced air circulation. An example is shown in Fig. 51. External anode valves are also designed for cooling by water circulation and are called *water-cooled valves.* They include types normally used as modulators, amplifiers or oscillators in high power transmitting circuits.* High temperatures developed at the anode in power valves are also often reflected in high grid temperatures, and means are therefore taken to allow for grid cooling by means of fins, extensions, etc., which increase the area for radiation.

Fig. 51.—*A typical power triode with external air-cooled anode—Type ACT6. Note the anode radiator fins.*

Considerations affecting power valve design.

Having taken into account the features of design necessary to allow a power valve to withstand an anode voltage and dissipation adequate for the purpose required, other features of design must allow for an adequate anode current to enable the necessary power to be developed. This means first that the cathode must have ample electron emission at the temperature of operation to satisfy the full peaks of anode current without signs of saturation, and secondly that the internal resistance (anode impedance) of the valve must be sufficiently low to allow full advantage to be taken of the available cathode emission without resort to excessively high anode voltages. From an examination of the characteristics of a triode, it can be shown that in order to obtain the maximum power, the load resistance is usually between a value equal to, and twice, that of the valve internal impedance at the working point, and hence to avoid the need for an excessively high load resistance, which might be difficult to obtain in practice, it is important that the impedance of a triode valve used as a power amplifier be kept as low as possible.

Next, because of low internal resistance and high anode current, we arrive at the necessity for ample total cathode emission. With a bright emitting tungsten filament the large total emission required often calls for a very considerable filament diameter and consequent heavy filament current. In very large valves it may be necessary to cool the filament lead-in wires by a forced air or water circulating system. The emission reserve of a thoriated tungsten filament being considerably

*See frontispiece illustration.

higher, and that of an oxide coated cathode higher still, the advantages of these are such as to make their employment very desirable in all cases where circumstances permit.

A further consideration in the design of a power valve is the *sensitivity* required, although this is usually of secondary importance to the undistorted power output. By sensitivity is meant the output power available in relation to the grid voltage input. As power output is dependent on change in anode current, the sensitivity becomes a question of the relationship between anode current change and grid voltage change, or, in other words, a question of mutual conductance. The mutual conductance of the power valve decides whether an additional degree of amplification is required between the original signal and the grid voltage input to the valve; it is often better to provide an additional stage of voltage amplification rather than complicate the structure of the power valve in an attempt to achieve high mutual conductance, owing to the other and more vital considerations of heat dissipation and electrode clearances which have been discussed.

Fig. 52(a).—A typical small power triode, 15 watts anode dissipation—Type PX4.

Fig. 52(b).—A typical medium power triode, 25 watts anode dissipation—Type PX25.

Fig. 52(c).—A typical medium power triode, 100 watts anode dissipation—Type DA100.

Finally, for absence of amplitude distortion in the output waveform, the question of linearity in the valve curves at high anode and large negative grid voltages is a factor of importance in the choice of a suitable electrode system.

CHAPTER 9

MULTI-ELECTRODE VALVES : TETRODES : PROBLEMS OF AMPLIFICATION AT HIGH FREQUENCY : THE SCREENED-GRID VALVE : THE PENTODE : VARIABLE-MU : TETRODES AND PENTODES AS DETECTORS.

There are, broadly speaking, two main classes into which multi-electrode valves may be said to fall :

(1) That in which the various electrodes are related to a single cathode to anode electron stream.

(2) That in which there is more than one cathode to anode stream involved.

There are, in addition, single-electrode system valves with a multi-purpose, and multi-electrode system valves with a single purpose. The difference between the two main classes usually implies that the second—that involving more than one main cathode to anode stream—consists merely of a combination of entirely separate (from the mechanical point of view) valve electrode systems sealed into a common envelope. Each of such systems may usually be considered as a separate unit as regards its operation. The combination of such dual or multi-systems into a common envelope is usually done for commercial convenience, although operating considerations sometimes arise which may render such a combination beneficial.

It is the former of these two classes—that involving a multiple electrode system relating to a common electron stream—which we are now going to examine. In such a group, two or more of the electrodes always function as controlling elements of the cathode to anode electron stream ; the voltages of the electrodes are always those existing between the electrodes and the cathode (or filament). Owing to their controlling function, the various electrodes additional to the cathode and anode are usually referred to as " grids." One of the grids is connected to the signal input circuit and is called the *control grid*, while in general each of the other grids is connected, perhaps with a fixed positive or negative potential relative to the cathode, to one of the three main electrodes—anode, control grid, or cathode. The characteristics of the valve will depend on how the auxiliary grids are connected ; if there are no external impedances in the auxiliary grid circuits, the valve is virtually a triode as far as the external circuit is concerned ; if there is an impedance included in any of the auxiliary grid circuits, such a valve is not the equivalent of a triode.

The tetrode.

A multi-grid valve (of the common cathode-anode stream class) having one auxiliary grid in addition to the control grid is usually referred to as a *tetrode*, to indicate a four-electrode system. Practical tetrodes are usually divided into three groups :

(1) Those in which the auxiliary grid is made to serve the purpose of decreasing the anode-cathode resistance (or reduction of the valve internal impedance). This application will not be considered further in this review.

(2) Those in which the auxiliary grid is employed as a means of injection into the main electron stream of an A.C. potential which can modulate the cathode-anode current. This is sometimes made use of in " frequency changers " which will be referred to later.

(3) Those in which the auxiliary grid serves to increase the anode-grid resistance to high frequency currents—or acts as a " screen " to the grid, with respect to the anode.

It is the third type of tetrode which we must now consider in some detail—that in which the auxiliary grid is used to " screen " the anode electrostatically from the grid.

Valves for amplification at radio frequencies.

The efficiency of any ordinary kind of rectifier acting as a detector of radio frequency signals varies as the square of the signal voltage, and it is this feature together with the improvement in frequency selectivity also made possible, which makes H.F. amplification of the input voltages *before* detection so useful.

The necessary condition for voltage amplification is that the impedance of the external anode circuit must be appreciable with relation to the internal anode

resistance. At low frequencies a high magnification per valve is not difficult of attainment, but at high frequencies, unwanted valve and lead capacities make it necessary to balance these out with inductances to obtain the desirable high external impedance. A resistance load R as in the circuit Fig. 53 will result in very small amplification at high frequencies due to the low impedance of the shunt capacity represented by C, but if a certain value of inductance is included, as shown by L, a high amplification is possible at the resonant frequency of C and L, which form a tuned circuit. Thus, tuned circuits become essential for adequate amplification at high frequencies.

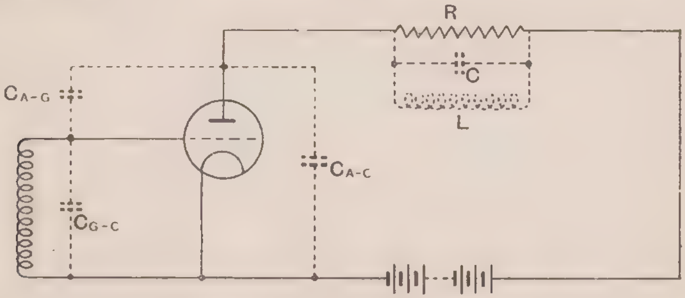


Fig. 53.—Circuit showing losses at radio frequency, caused by : C, *shunt capacity of resistance ;* C_{A-G}, *anode-grid capacity of valve, coupling output voltage to input voltage ;* C_{A-C}, *anode-cathode capacity additive to* C *;* C_{G-C}, *grid-cathode capacity in shunt across input.*

One of the principal drawbacks, however, to efficient and stable voltage amplification at high frequencies is the coupling which occurs between the output and input tuned circuits of the amplifying valves, mainly due to the anode-grid capacities of the valves. The higher the voltage magnification—due either to more efficient tuned coils, or more efficient (higher mutual conductance) valves—the greater the effect of these couplings in introducing positive feedback, and consequent instability.

A method of reducing the effect of this coupling in an endeavour to increase stable amplification at high frequencies is to design the valve in such a way that the capacities of the lead out wires, supports, and base are largely reduced by avoiding a common outlet for the grid and anode connections, the residual capacity being between the actual anode and grid.

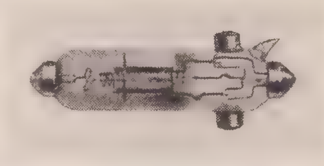


Fig. 54.—An early triode for high frequency amplification.

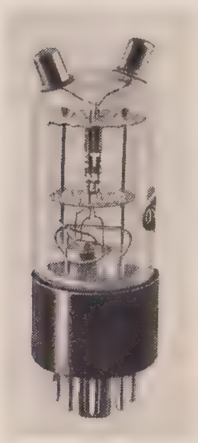


Fig. 55.—A triode of low grid-anode capacity for high frequency circuits—Type DET20.

Such a triode valve is illustrated in Fig. 54, this having been issued commercially in the early days of radio ; another valve, of more recent design, is shown in Fig. 55. Although such valves may prove efficient oscillators, in an amplifier a multiplicity of stages is in general necessary to achieve reasonable overall gain, and this again introduces difficulties —notably due to the capacities and inductances of connecting wires, and to common coupling through the H.T. supply.

An alternative method of obtaining stability in amplification at high frequency is that of artificially neutralising the anode-grid coupling by another and similar value of coupling external to the valve, in opposite phase from the coupling

resulting from the valve capacity itself. Such methods of *neutralising* the anode-grid capacity suffer from the disadvantage of being frequency-selective, that is, in practice they are only fully effective at one given frequency. The anode-grid capacity is therefore a real limitation to the maximum amplification obtainable at high frequencies, but this capacity may be greatly reduced by the introduction of an *electrostatic screen* interposed between the anode and grid within the valve.

The screen-grid tetrode.

The addition of the screen converts the triode into a tetrode, which can then be described as a *screen-grid tetrode*, the term " screen-grid " or " screened valve " being applicable to all forms of multi-electrode valve employing this principle. The introduction of the screen grid can be made to reduce the anode-grid capacity from values of from 5 to 10 micro-microfarads for a typical " general purpose " triode, to values of the order of 0.01 to 0.001 micro-microfarad, depending on the method of construction. The extent of the screening effect depends on the construction of the shielding electrode and the physical placing of the anode and grid lead wires relative to each other. In practice the screen is usually made to surround the grid as far as possible, with apertures covered by very fine mesh opposite the region of the cathode-grid system from which electrons are escaping. The anode has as small a surface as is possible.

As with the H.F. triode, so also in the screen-grid valve the greatest benefits in reduced anode-grid capacity are obtained when electrical proximity between the

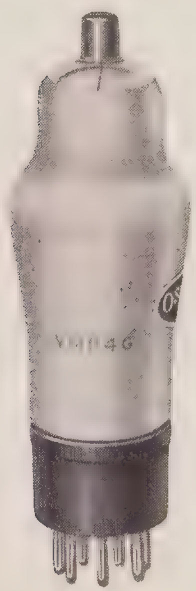


Fig. 56(a).—A screened valve in which the anode is brought to a separate connector—Type VMP4G. Illustration shows metalised bulb.

Fig. 56(b).—A screened valve in which the control grid is brought out to a separate metal connector at the top of the bulb—Type KTW61.

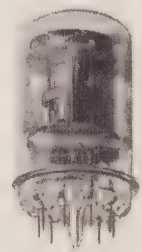


Fig. 57(a).

Fig. 57(b).

Fig. 57(a).—A screened H.F. valve using a " ring seal " method of construction in which all the electrodes are brought to a common base and special screened shields are employed. Illustration shows incompleted valve without earthed " can " or locating spigot.

Fig. 57(b).—A valve of the type shown in Fig. 57(a), but fitted with earthed screening " can " and locating spigot. Useful for the U.H.F. range.

anode and grid lead wires is avoided. Two designs of screen-grid valves are shown in Figs. 56(a) and 56(b), the former in which the anode lead is separated from

a common support for the cathode and screen, and the latter in which the grid is the isolated connection. The question as to whether the grid or anode should have the isolated electrode connection is probably one of manufacturing convenience and circuit layout.

Other designs of screened valves have been developed in which both grid and anode lead wires are taken to a common base on a "ring seal," and special screened shields are used. An example, useful for the U.L.F. range, is shown in Fig. 57(b).

Let us now see what occurs to the characteristic of the valve as a result of introduction of an auxiliary (screen) grid placed at a positive potential in the

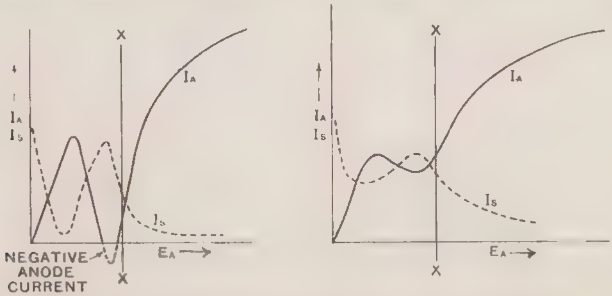


Fig. 58.—Typical screen-grid tetrode characteristics.

electron stream between grid and anode. Fig. 58 shows two typical E_A–I_A curves for a fixed grid potential and fixed screen potential, the screen potential being lower than that of the anode—say about half its value. Consider the changes in I_A and I_S to the left of the vertical line XX. At very low anode voltages the valve operates as a normal triode, increasing anode voltages increasing the electron velocity and so allowing more electrons to escape from the space charge. The screen, being at a relatively high voltage, draws current, known as the *screen current* I_S, which is reduced as E_A rises, due to some of the electrons being drawn through the screen to the anode. Owing to the close mesh of the screen, the anode is only able to rob the screen of electron current and not by itself to produce an electron current, and in consequence the sum of the two currents to the anode and screen will be approximately the same as the current to the screen would be if the anode were removed.

A further increase in anode voltage speeds up the electrons, which bombard the anode with a sufficiently high velocity to produce secondary emission from the anode. These secondary electrons leave the anode and pass to the screen grid, causing a reduction in anode current and a rise in screen current. Increasing the anode voltage still further brings the anode and screen voltages to a common value at which point a steep rise in anode current occurs corresponding to a similar steep fall in screen current, due to the deviation of the screen current to the now equal potential anode. This occurs at XX in Fig. 58. The higher the screen voltage in respect to the anode voltage, the farther to the right in the curve will XX occur.

The portion of the tetrode characteristic useful for most purposes is restricted to that well to the right of XX, in which region the anode current line becomes practically straight and the *anode current is nearly independent of the anode voltage.* If there were perfect shielding and no secondary emission from the screen, the curves would be perfectly flat. The flatter the curve, that is the more nearly I_A becomes independent of E_A, the higher is the internal resistance R_A of the valve.

If the valve were a triode, such high values for R_A would greatly restrict the practical magnification owing to the high anode voltage necessary, and the low

mutual conductance resulting from this high resistance. In a tetrode, however, such values for R_A may be obtained combined with a high mutual conductance, and as mutual conductance is equal to $\frac{m}{R_A}$, this makes possible very high values of amplification factor m, and greatly increased voltage amplification at normal "H.T." voltages.

Operating considerations in a screen-grid tetrode.

The effect of variation in screen voltage E_S (or E_{G2}) is important, and Fig. 59 shows the curves of a typical screened tetrode, anode current being plotted against anode voltage for a low and a high screen voltage. Several points of interest arise :

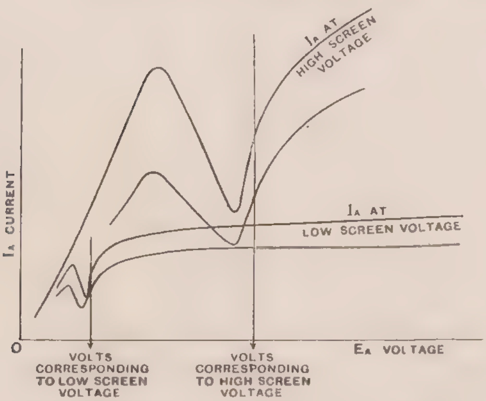


Fig. 59.—Effect of variation in screen voltage on given tetrode.

(1) The screen voltage should at no time be allowed to equal or exceed the anode voltage.

(2) Low screen voltages extend the flat portion of the characteristic to the region of lower anode voltages, while high screen voltages reduce the range of anode voltage for linear operation.

(3) Low screen voltages result in a much higher "m" value for a given set of conditions than do high screen voltages.

(4) Under working conditions the standing anode current increases with the screen voltage.

(5) Higher screen-to-anode voltage ratio results in a lower internal resistance.

(6) Higher screen voltages result in a higher mutual conductance.

(7) Due to the restriction of the "working characteristic" with high screen voltages, arising from secondary emission, and to restricted anode current with low screen voltages, such a tetrode is limited even as a voltage amplifier, and is of little or no value for power amplification.

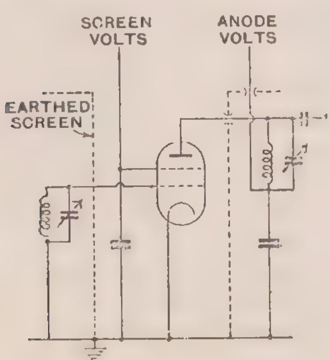


Fig. 60(a).—Screen-grid tetrode in H.F. amplifying circuit using tuned anode loading.

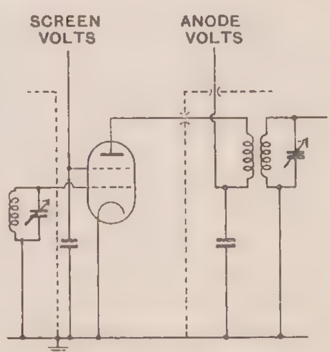


Fig. 60(b).—H.F. amplifying circuit using tuned transformer loading.

In radio frequency amplifiers, this type of valve is quite suitable, since the circuits illustrated in Figs. 60(a) and 60(b), for a tuned anode load and a tuned transformer, offer a high impedance at the resonant frequency, and thus enable the maximum voltage amplification of the valve to be closely approached. Owing to the practicability of a very much lower anode-grid valve capacity than in a triode, such increased amplification may be realised without regeneration due to positive feed-back, provided that adequate shielding between the circuit components is also introduced.

Pentodes and power tetrodes.

We have examined the advantages of the screen-grid tetrode ; its limitations as a voltage or power amplifier due to secondary emission have been pointed out. The means of overcoming these will now be considered.

In practice, in order to retain the essential features of a tetrode, and at the same time increase its voltage or power handling capacity with limited anode voltages, means must be found to suppress, or materially reduce, the secondary emission from the anode. There are several methods of achieving this :

(1) The valve may be so designed as to operate with a low screen voltage and small grid-screen clearance (see Fig. 61).

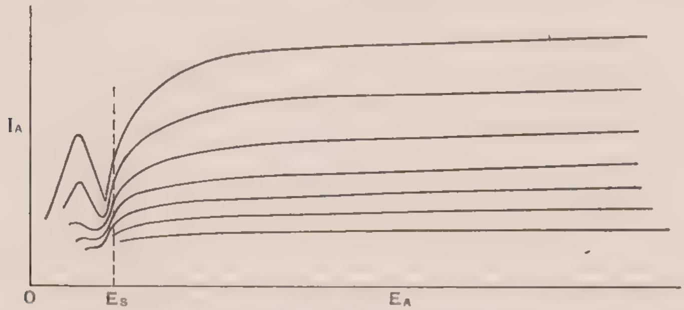


Fig. 61.—Tetrode with low screen voltage and close grid-screen clearance.

(2) An extension of method (1) in which the anode-screen clearance is made very large in addition to making the grid-screen clearance small, combined with the use of an open-meshed screen.

(3) The anode surface within the electron stream may be coated with a material which is not conducive to secondary emission.

(4) An additional electrode may be introduced in the electron stream, between screen grid and anode, to which may be given a negative potential with respect to the anode and screen and thus prevent low velocity secondary electrons getting back to the screen. The auxiliary electrode may be so designed of open mesh wire as not to interfere with the passage of high velocity primary electrons towards the anode.

By reason of this additional " grid " such a valve contains five electrodes and is termed a *pentode.*

(5) Additional electrodes may be provided between screen grid and anode, but not in the electron stream, their function being to introduce an electrostatic field in the neighbourhood of the anode and cause a " focussing " effect on the primary electrons which will, by virtue of such intensified space charge, tend to repel the secondary electrons leaving the anode. Such a valve is often termed a *beam tetrode.*

Of the methods outlined, (4) and (5) and sometimes (2) are normally employed in practice. True pentode valves designed to achieve the aim of suppression of secondary emission from the anode do this by reason of a *suppressor* grid which is made in the form of an open-meshed electrode which is normally connected to a point in the circuit at cathode or at H.T. negative potential, but which may alternatively be connected to the control grid in cases where this is at negative potential to the cathode.

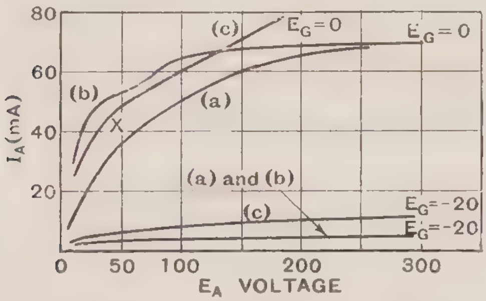


Fig. 62.—Effects of modification to design of suppressor grid and screen grid in pentode.

(*a*) *Pitch of suppressor grid too small—primary electrons fail to reach anode when anode potential is low.*

(*b*) *Pitch of suppressor grid too large—some secondary electrons reach the screen at low anode potentials.*

(*c*) *Too open screen grid—allowing the potential of the anode to affect the field near the cathode, thus reducing the internal resistance.*

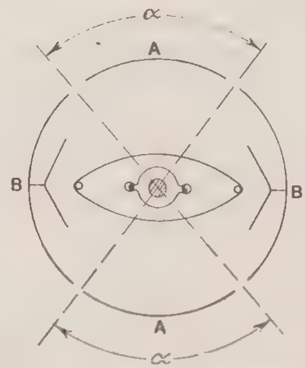


Fig. 63.—Tetrode with " earthed " plates to suppress secondary emission.
AA *represents anode in two segments of a cylinder.*
BB *represents two additional electrodes at zero or negative potential to concentrate the electron stream between the boundaries enclosing the angle* $\propto$

Fig. 62 shows the effect of modification to the design of the suppressor and screen grids in a pentode. The point X at which the change in curvature (more or less sharp) takes place is known as the " knee " of the curve and limits the extent of anode voltage swing under normal " Class A " conditions of amplification, and therefore controls the available power output under such conditions. It is obviously desirable for the " knee " to occur at as low an anode voltage as possible and for the curves to be as flat as possible beyond the knee.

Fig. 63 illustrates method (5), in which earthed plates or rods are provided in proximity to the anode, but not in the main electron stream. Another design makes use of an electrode structure with two additional electrodes held at zero or negative potential, which concentrate the electrons into a beam; this attains the desired result in a manner similar to that described above, but the " beam " formation gives added force to the prevention of secondary emission by concentration of the space charge around the anode.

Such valves have been termed commercially " kinkless tetrodes," as distinct from the true screen grid tetrode without secondary suppression, but for all practical purposes can be considered as similar to pentodes from the point of view of operation.

Comparison between pentodes and triodes in amplifying circuits.

The essential differences existing between the performance of triode and pentode (or power tetrode) valves may be said to be :

(a) In pentodes and tetrodes the principal harmonic content normally introduced as distortion is the third harmonic, whereas in triodes it is the second harmonic.

(b) In pentodes and tetrodes, a reduction in load resistance *decreases* the power output and increases the harmonic distortion, whereas in triodes a reduction in load resistance tends to *increase* the power output and increases the distortion to a greater extent.

(c) In pentodes and tetrodes an increase in load resistance tends to increase the power output with considerable increase in distortion, whereas in triodes an increase in load resistance *decreases* both the power output and distortion. See Figs. 64(a) and 64(b).

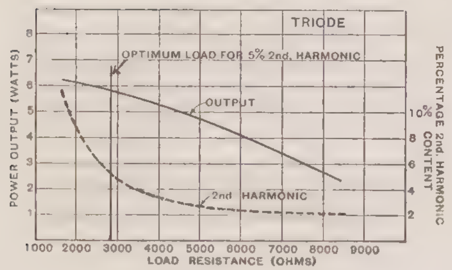


Fig. 64(*a*)

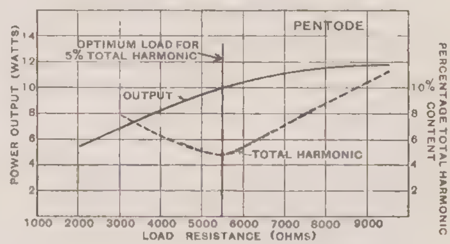


Fig. 64(*b*)

Showing comparison between typical triode and pentode valves in power output and harmonic distortion for varying load resistance values.

(d) Owing to the high internal resistance, pentodes and tetrodes are essentially constant current devices, in which the internal resistance is always high in proportion to the load impedance. The power triode, owing to its comparatively low internal resistance, is essentially a constant voltage device in which the load impedance (varying with frequency) causes considerable current fluctuation with frequency.

Should the load in the anode circuit be reactive, and therefore variable with frequency, the pentode will tend to maintain a constant current, and thus any points of maximum impedance occurring throughout the range of frequencies will cause peaks of voltage at such points. This, combined with a greater tendency to amplitude distortion than in the case of triodes, renders a pentode or tetrode power amplifier more critical in design than one using power triodes.

It will be realised that for maximum power output combined with minimum introduction of harmonic content, the load impedance requires careful adjustment to the optimum for the design of valve and its operating voltages ; this is usually effected by means of a suitably designed transformer to match the value of the actual load. The ratio of such a transformer is given by the expression :

$$\frac{\text{Secondary turns}}{\text{Primary turns}} = \sqrt{\frac{\text{actual load resistance}}{\text{optimum anode load resistance}}}$$

Excessive peak voltages may be developed across the load and valve, should the impedance of the load attain a high value and the valve simultaneously be fully modulated. Such high voltages may result in damage to the load or to the valve by spark-over, and so a limitation of load impedance becomes necessary with valves of the types under discussion.

Another important point to bear in mind in the operation of power pentodes to secure the maximum output is the maintenance of constant screen grid voltage ; it is undesirable to derive the screen voltage, where it is lower than the anode voltage, by the drop in voltage across a series resistance from the source of anode power. A potentiometer designed to carry a current substantially greater than the average

screen grid current should be employed to avoid risk of a reduction in the actual power output.

Pentodes for radio frequency circuits.

In the application of pentodes (and " kinkless " tetrodes) to voltage amplification at high frequencies, the most important consideration, as with the screened tetrode, is the reduction in anode-grid capacity, but the main advantage over the true screen-grid tetrode is that the necessity for a high anode-screen voltage ratio may be avoided. Thus an H.F. pentode will, if necessary, operate successfully at lower anode voltages than will a screen-grid tetrode, and a similar voltage may be applied to both anode and screen. The removal of the secondary emission " kink " also increases the practicable voltage amplification, and extends the utility of the screened H.F. amplifier valve in this respect.

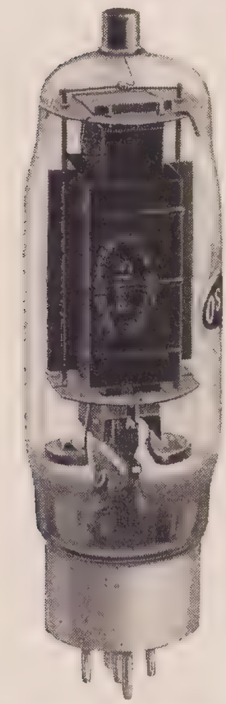


Fig. 65.—A typical power pentode for H.F. oscillatory circuits—Type PT15.

In an amplifier of radio frequency voltages, the degree of amplification may be controlled in any of the following ways :

(1) By variation of input to the grid, either by means of a potentiometer or a variable series condenser. The former method is efficacious but serves to introduce extra damping across any tuned circuit across which it is applied; the latter ceases to be a satisfactory method on shorter wavelengths, and alters the tuning constants.

(2) By variations to screen grid voltage. This affects the mutual conductance of the valve and therefore its amplification. A large reduction in screen voltage is necessary, however, to reduce the overall " gain " with high efficiency tuning coils, and under such conditions the input acceptable without severe distortion is extremely small. The method is not applicable to control of amplification with a large signal input.

(3) By increase in negative grid bias, which increases the internal resistance and reduces the mutual conductance.

The method (3), or (3) in combination with (1), is in practice most commonly employed. The adoption of control by grid bias is, however, liable to introduce serious distortion of a strong signal, the effects being :—

(a) Distortion due to non-linearity in the relation between H.F. input and output voltages.

(b) Increased " cross modulation."

(c) Increased hum due to introduction of mains modulation into the carrier (in mains operated amplifiers).

The " variable-mu " valve.

Cross modulation (or " cross talk "), is a term denoting interference originating by modulation between two or more signals. It may take the form of " beating " between two signals whose frequencies differ slightly from each other and from that to which the receiver is tuned ; alternatively, if sufficient selectivity is provided to

prevent interference when the desired signal is unmodulated, both it and an unwanted signal of close frequency will be heard simultaneously when the desired signal is modulated. In control of amplification by grid bias, therefore, it is necessary to prevent any sharp " bends " in the I_A–E_G curve at points where the mutual conductance is low; this is achieved to a great extent in practice by the use of the so-called *variable-mu* valve.

The detrimental effects, as described above, in amplification control by means of negative grid voltage, can be much reduced by choosing a low mutual conductance, but the effect of this is seriously to limit the permissible amplification on weak signals. It would therefore be a practical solution of the problem to operate two valves in parallel, the one with a very low and the other with a high value of mutual conductance. This result is in effect achieved with the variable-mu valve, in which the control grid is so designed that at small grid voltage it exerts a large control on the anode current, but at large grid voltage the grid control is small. In this way a high mutual conductance may be obtained at low bias voltages, giving increased sensitivity with small input signals, while the input signal which can be accepted, without excessive non-linearity, may be considerable at high bias voltages.

The control of amplification by grid bias becomes an essential feature of a receiving circuit in which the amplification at high frequencies is controlled by the strength of the input signal, so that the audio frequency output after detection remains more or less constant for a considerable range of input voltages. This condition, known as *automatic volume control*,* is completely successful only when the controlled amplifying valves are of the variable-mu type. Weak signals are amplified on the steep portion of the curve; strong signals cause the negative bias to increase so that the operating point moves to a portion of the curve having a small slope.

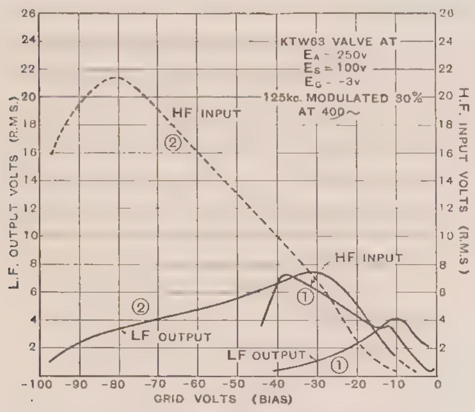


Fig. 66.—Curves relating H.F. input volts and L.F. output volts to negative grid bias for " variable-mu " screened valve.

1 *With fixed screen voltage.*

2 *With series screen resistance.*

Fig. 67.

A typical 2-volt battery " variable-mu " H.F. pentode—Type W21.

The conditions for variation of mutual conductance with grid voltage described above are on the assumption of a fixed screen voltage; when screen and anode voltages are obtained from a common H.T. " line " voltage, this necessitates the use of a potentiometer, through which, as mentioned before, the steady current must be

*See page 70.

sufficiently high to offset changes of screen current with change in bias. It is sometimes desired to increase the voltage handling capability of a variable-mu valve at the expense of " control " so that greater outputs may be obtained under conditions when a large input signal voltage is available. This may conveniently be done by supplying the screen current through a series resistance, which results in larger signal handling ability and greater voltage output, and typical characteristic curves for this condition are shown in Fig. 66.

The tetrode or pentode as a detector.

An application of the screened pentode or tetrode of particular interest is that of a detector. A screened valve used in this way may be said to possess the following advantages over the triode :

(a) In general, a somewhat higher sensitivity is obtained, depending on the anode and screen voltages applied.

(b) The lower anode-grid leakage capacity of the screened valve decreases the shunt resistance across the tuned circuit.

With a screened valve as detector, for example, it is possible by reduction of damping to effect a higher degree of frequency selectivity and also to permit better " ganging " of tuned circuits over a wide band of wavelengths.

CHAPTER 10

Multiple Electrode Valves (continued) : Valves for Frequency Conversion in the Supersonic Heterodyne : Hexodes, Heptodes and Octodes : Multiple Purpose Valves : Diode-Triodes for A.V.C.

In the last chapter we discussed certain types of multiple electrode valves, with particular reference to screened tetrodes and pentodes. In these valves, however, such electrodes as are introduced additionally to the control grid and anode have no alternating or signal voltages applied to them. In a valve with a single cathode-anode path, it may occur that there is an external circuit impedance in

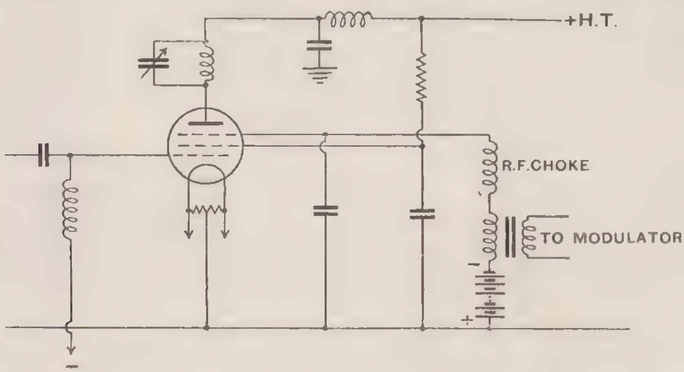


Fig. 68.—Circuit illustrating pentode as driven H.F. power amplifier with suppressor grid modulation.

series with one of the auxiliary electrodes, so that a control voltage is exerted additional to that on the control grid. For example, in a pentode, a control voltage may be applied to the suppressor grid, which may take the form of an audio frequency signal ; this becomes injected into the electron stream via the suppressor grid and may serve to modulate a radio frequency voltage generated in the grid and anode circuits of the valve connected as a simple oscillator (Fig. 68).

Special valves have been developed for purposes similar to that above, where two alternating voltages of different frequency are applied to separate grids of the valve to control a single cathode-anode stream. The most common use of such types is as *frequency changer*, or *mixer* valves in superheterodyne receivers, and in order to appreciate the necessity for the characteristics and design of such valves a knowledge of the supersonic heterodyne principle is required.

Principles of the superheterodyne.

When we want to receive high frequency signals, there are two main problems to overcome : first, the comparative inefficiency of a detector system on very low input voltages, and secondly, difficulties of clear reception of a wanted signal free from interference from other signals on adjacent frequency channels. The solution of both these requirements necessitates pre-detector radio frequency amplification of the carrier, and it was with the object of achieving a greater practical pre-detector amplification, and at the same time restricting this to a narrow band of frequencies, that the principle of the " superhet " was evolved.

In brief, the system depends on changing the frequency of the incoming modulated carrier to a carrier wave of some other frequency which may be amplified more conveniently than the original signal picked up by the receiving aerial. The frequency to which the signal is converted is usually some intermediate value between that of the radiated wave and its audio frequency modulation (although it may be at a frequency higher than the signal frequency in certain circumstances). The frequency after conversion is termed the *intermediate frequency*. It is so chosen that it does not come within the radio frequency band, or bands, being received, and it is the use of this intermediate frequency (I.F.) which gives to the superheterodyne its possibilities of high pre-detector amplification, since the intermediate frequency is arranged to be *constant*, despite the very wide range of radio frequencies in which the received signal may lie. This fact is an exceedingly important contribution to the simplicity of such an amplifier.

Due to this constancy, the intermediate frequency amplifier may, if desired, be sharply tuned without difficulty, and further, the use of a frequency lower than that employed for signal transmission reduces back coupling effects and enables the tuned circuits to be so designed as to produce a high gain per stage without instability. Hence it is possible by this method to achieve both high amplification and selectivity to degrees which would be exceedingly difficult—if not impossible—with circuits tuning over a range of signal frequencies.

Frequency conversion.

Now the essential feature of the superheterodyne is the *frequency conversion stage*, in which the received voltage is combined with a voltage from a local oscillator and converted into a voltage at the intermediate frequency. The function of the frequency converter is therefore to change the frequency of the received signal, whatever it may be, to that of the fixed frequency I.F. amplifier.

The frequency converter consists of a variable frequency oscillator and a " mixing " element. Although the input to the frequency converter consists of only two frequencies, the output contains many more ; there will be currents in the anode circuit of the valve of signal frequency, of oscillator frequency, of a frequency equal to the sum of the input frequencies, and of a frequency equal to the difference of the input frequencies. In addition there will generally be harmonics of all these, and other frequencies besides. After heterodyning the signal by the oscillator frequency, the frequency corresponding to the difference between the oscillator frequency and the signal frequency is generally selected in the output of

the first detector. Tuned circuits are also provided in the I.F. amplifier which resonate to the selected frequency, and hence give the maximum gain round about this frequency.

A measure of the sensitivity of a frequency changer valve in a superheterodyne (although not the final criterion of efficiency) is termed the *conversion conductance.* This may be defined as :

$$g_c = \frac{\text{Amplitude of I.F. component of anode current}}{\text{Signal voltage input}}$$

It is the counterpart of mutual conductance in amplifying valves. Conversion conductance is usually measured in terms of microamperes per volt, sometimes referred to as " micro-mhos."

Valves as frequency changers.

Varied forms of frequency changers involving methods in which oscillation, " mixing," and detection are effected in a common cathode-to-anode stream, and others in which the local oscillations are produced from a separate source, have been widely employed in practice, and some of the more common forms will now be described, omitting earlier types which are only of historical interest.

1. *A single valve of the screened tetrode or pentode type, as self oscillating detector.*

This circuit, variants of which are shown in Figs. 69(a) and 69(b), is sometimes

Fig. 69(*a*).—*A screen grid tetrode frequency changer in which oscillation takes place between the anode and control grid circuits and the coupling coil is included in the cathode lead.*

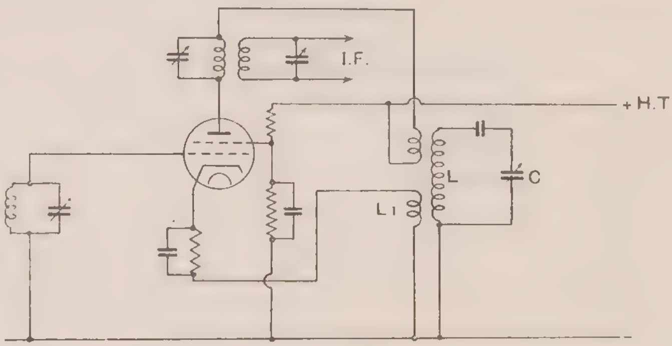


Fig. 69(*a*).

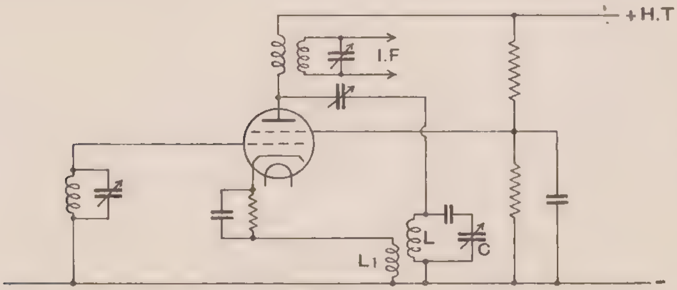


Fig. 69(*b*).

Fig. 69(*b*).—*A typical detector-oscillator mixing circuit for a tetrode screen-grid valve.*

known as the cathode injection mixer circuit, and in it the input signal is rectified by anode bend detection. So far as efficiency is concerned, the circuits are satisfactory, but there are several serious drawbacks to their general utility such as serious interaction between the oscillator and signal-frequency circuits, and a risk of radiation from the aerial. In addition, considerable variation in sensitivity

over the tuning range results from the difficulty of designing a suitable stable oscillator system.

2. (a) *The heptode, or pentagrid frequency changer.*

This form of frequency changer has attained widespread application in practice. The heptode is a multiple electrode valve having a common cathode-anode stream, and a structure incorporating five " control " electrodes, or seven electrodes in all, from which it derives its description " pentagrid," or " heptode."

The mechanism of a typical heptode (a circuit incorporating which is in Fig. 70)

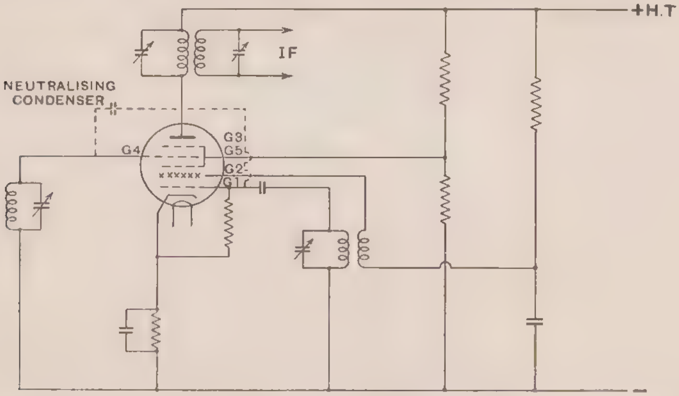


Fig. 70.—Typical circuit for a heptode or " pentagrid " frequency changer.

G1 *is the oscillator grid.*
G2 *is the oscillator anode.*
G3 *and* G5 *are the screens joined internally.*
G4 *is the signal input grid.*

is briefly that the electron current is first modulated at oscillator frequency by an inner electrode G1, and the electrons are then accelerated by the screen-grid G3, towards the control grid G4 on which are the incoming signal voltages. This screening grid G3 is provided between G2 and the control grid G4 to prevent electro-static coupling between these two electrodes, and is maintained at a positive potential. The screen is extended to shield also the main anode from the control grid, and as such comprises the extra grid G5 (the screen-grid familiar in a tetrode). In practice, due to the high velocity of bombardment of G3, secondary electrons are emitted from the screen and are directed towards the *oscillator anode* G2. The oscillator anode current is then mainly the result of secondary emission from the screen.

The signal grid G4 controls not only the electron stream emitted from the main cathode, but it also controls electrons derived from the *virtual cathode*, which may describe the electron " cloud " formed between G2 and G3. The electron current, on arrival at the main anode, carries components of the two frequencies, signal and oscillator, as well as the sum and difference frequencies; the anode circuit is then tuned to the desired I.F. (usually the difference frequency). It is usual to construct the oscillator anode G2 in the form of two wires parallel to the cathode, and it may be placed between the support wires of the inner grid G1 and the screen G3. This reduces interaction between the signal control grid and the oscillator section of the valve.

2. (b) *The octode frequency changer.*

As in the tetrode, where the addition of a suppressor grid is a means of suppressing secondary emission from the anode, so in the heptode a suppressor grid

is sometimes added between G5 and anode to give a similar effect (Fig. 71). With this arrangement the valve becomes an " octode "—a term derived from its eight electrodes. In essentials the behaviour of heptodes and octodes as " mixer " valves is similar.

Heptodes and octodes are reasonably free from interaction between signal and oscillator voltages on medium and long-wave reception (from 100 metres wavelength upward), but on short wavelengths, space charge coupling between the oscillator and signal grid becomes of increasing importance, and seriously limits their application at high radio frequencies.

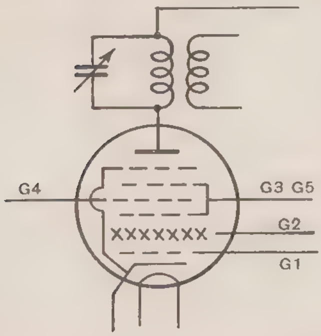


Fig. 71.—Octode with sixth grid providing suppressor action.

An extension of the efficient conversion range is sometimes achieved by means of a neutralising capacity (about 1 $\mu\mu$F) between the high potential end of the oscillator coil and the signal grid (shown dotted in Fig. 70).

3. *The tetrode or pentode with separate source of local oscillations.*

The simplest and one of the earliest forms of superheterodyne circuit consisted of a triode valve operating as a leaky grid detector, into whose grid was injected the voltage of a local triode oscillator. The arrangement is not, however, used except at very high frequencies where other forms of mixers become inefficient. An alternative arrangement employs a screened tetrode or pentode as a mixer valve.

Fig. 72 shows a grid injection type of circuit, the output from a triode oscillator being coupled to the control grid of the mixer through a low capacity condenser and a resistance. Both the signal and oscillator voltages are impressed on the same grid. Grid injection suffers from the disadvantages of serious radiation, interaction, and difficulty of obtaining uniformity of oscillator voltage over the whole tuning band.

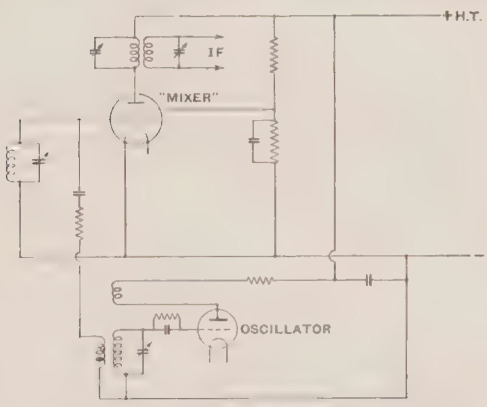


Fig. 72.—An example of grid injection of oscillator voltage into a screened tetrode " mixer " valve.

An alternative arrangement, which is commonly adopted in practice, is the injection of the oscillator voltage into the cathode circuit of the " mixer " valve. In effect, injection into the cathode circuit is very nearly the same as injection into the grid circuit, but as the injection takes place at the low potential (earthed) end of the grid-cathode circuit, radiation of the oscillator frequency is reduced (Fig. 73). The operation of cathode injection frequency changers is also limited by the occurrence of interaction.

Another system using pentode mixer valves with a separate oscillator is that employing either suppressor grid or screen grid injection. Suppressor grid injection with a pentode is shown in Fig. 74, and such a system gives the advantages of considerably less chance of interaction than with cathode injection. Owing to the low mutual conductance between suppressor or screen grids and anode, however,

a very considerable increase in oscillator voltage is required, with the attendant difficulties of tight coupling and generation of harmonics.

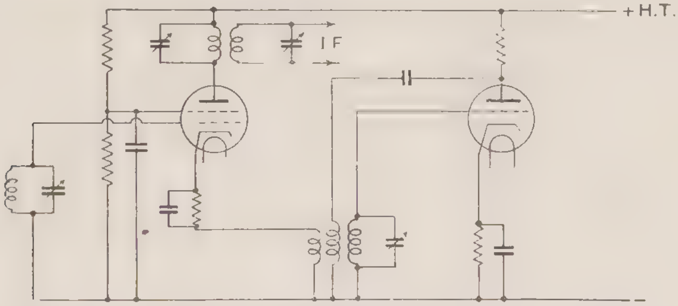


Fig. 73.—A method of applying cathode injection of oscillator voltage to a " mixer " valve, using an indirectly heated screened tetrode with the oscillator output coupled in series with the cathode circuit.

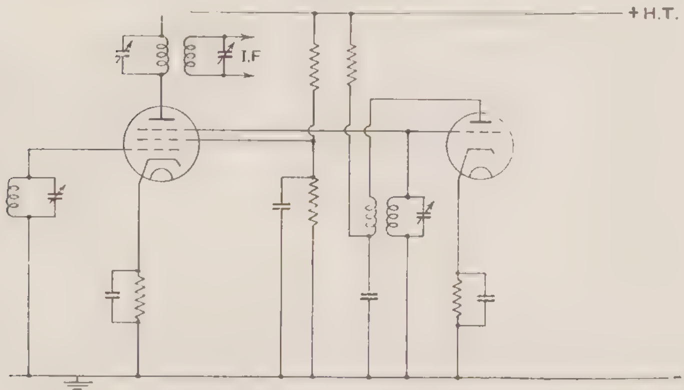


Fig. 74.—A system employing a pentode " mixer " valve with suppressor grid injection of oscillator volts.

4. (a) *The " mixing " hexode, or heptode, with separate source of local oscillations.*

Such valves are essentially of the high frequency screened tetrode or pentode type, in which the pitch of the third grid is so designed to obtain a good control of the electron stream, and thus overcome the drawback of the necessity for high oscillator voltages, which has been referred to above under pentodes with suppressor grid injection. This third grid may in this case be referred to as the *injector* G3 (Fig. 75).

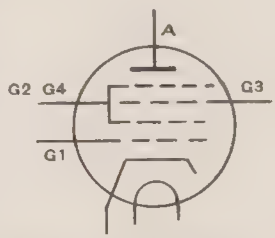


Fig. 75. — Diagrammatic representation of mixing hexode

A screen grid G4 is added between the injector grid and the anode, and is extended as G2 to shield the injector grid from the control grid G1, from which it will be seen that such a valve has six electrodes and thence derives its name *hexode*.

If an additional screen grid G5, at cathode potential, is inserted between G4 and anode, the valve becomes a *mixing heptode*. A typical circuit using a mixing heptode (or hexode), with a separate triode oscillator, is shown in Fig. 76.

It is important to distinguish the operating mechanism of such a mixing hexode or heptode from the self oscillating heptode or pentagrid already discussed in (2) above. In the latter we have seen that a serious limitation occurs at high

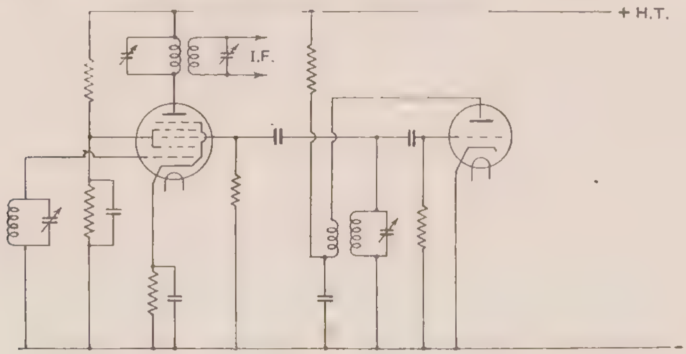


Fig. 76.—A typical circuit comprising a mixing heptode with separate triode oscillator.

radio frequency signal inputs due to interaction caused by the influence of oscillator frequency voltages on the control grid; in the mixing hexode the first grid G1 is the signal grid, while the oscillator frequency is applied to G3. Interaction between mixing and signal grids may still occur, though due to the fact that there is no electron coupling between the oscillator grid and the signal grid, the amplitude of the oscillator voltage transferred to the signal grid is small.

4. (b) *The heptode, or pentagrid, with separate oscillator.*

In any frequency changing circuit employing self-oscillating heptode valves, tuning the signal circuit through the resonant frequency of the oscillator circuit causes variations in the oscillator frequency, because of interaction between signal and oscillator grids, as we have seen; this effect is often called " pulling."

It is possible to reduce the interaction to a fraction of its original value by removing the undesired electronic coupling present in all self-oscillating heptodes, and this may be done by coupling to the oscillator grid an oscillator voltage generated by a separate source. A typical circuit is given in Fig. 77. The use of a separate oscillator makes it easier to supply the necesssary oscillator voltage required to maintain the efficiency with short wave operation.

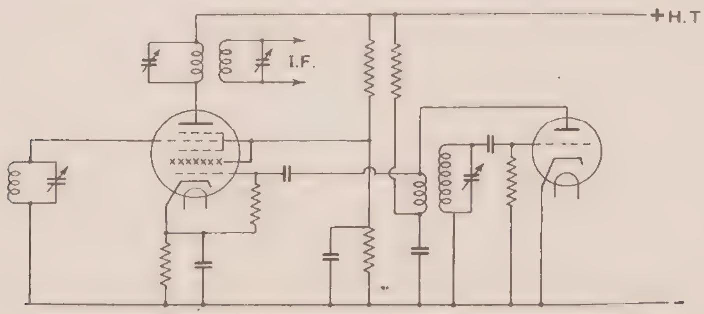


Fig. 77.—Circuit employing normal heptode or octode, but with separate oscillator for reduction of interaction.

5. *Valves of the multiple electrode type having separate cathode to anode streams for " mixer " and oscillator sections.*

The two principal classes of multiple electrode frequency changer valves designed on the dual system principle are the triode-pentode and triode-hexode combinations.

The design and manufacture of such dual function valves does not introduce any fundamentally different principles from those already discussed, such combinations being mainly for convenience in saving of space and the facility of a common socket connection. There may also be a slight advantage over the entirely separate valves for " mixing " and oscillation due to the absence of external connecting wires and consequent reduction in stray inductance and capacity. In

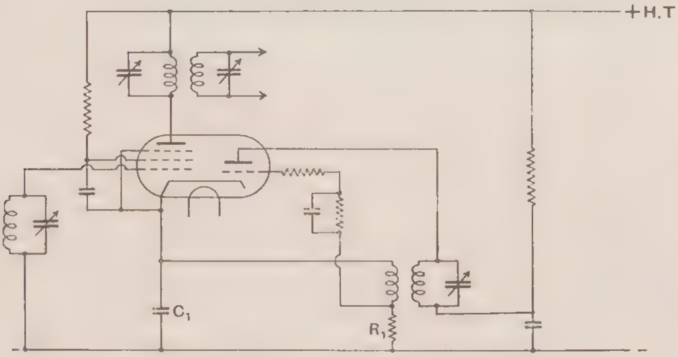


Fig. 78.—Circuit employed for combined triode-pentode valve as frequency converter with cathode injection of oscillator voltage.

these valves a common cathode structure may be employed, but there are two separate and distinct electron streams, one part of the cathode being employed for the " mixer " system and the other for the oscillator system. Alternatively the electrode systems may be mounted on two entirely separate cathode structures built on to a common support.

(a) The *triode-pentode* combination consists of a triode and screened pentode built into a common envelope, all the electrodes being brought out to separate connectors.

In the circuit shown in Fig. 78, the oscillator anode coil is tuned ; a condenser C_1 from cathode to earth acts as a shunt across the cathode coil and tends to produce a load which increases with frequency. Secondly, a potentiometer effect is obtained, the voltage across C_1 being applied to the pentode control grid, and so the heterodyne voltage, which normally increases with frequency, tends to be more constant, with a reduction in oscillator harmonics. A series resistance in the oscillator grid circuit also tends to reduce harmonics, and grid current overloading is avoided by a cathode resistance R_1 which provides a minimum bias. This arrangement is not suitable for short-wave reception.

(b) The *triode-hexode* or *triode-heptode* combination in one system (shown in Fig. 79) consists of a triode and the mixing hexode or heptode built into a common envelope, the injector grid G_3 of the hexode element being connected internally to the oscillator grid of the triode

element, and the oscillator grid and all the other electrodes being brought out to separate connectors.

In the circuit shown in Fig. 79, the oscillator grid coil is tuned, which is satisfactory in view of the small amount of interaction between signal and oscillator grid circuits ; an alternative is to tune the anode coil which sometimes results in greater freedom from " pulling " at the higher radio frequencies. To prevent parasitic oscillation at the high frequency end of each tuning range a resistance R may be used in series with the oscillator anode coil, its value being adjusted until the optimum oscillator voltage is obtained.

By suitable placement of the electrodes to reduce positive grid current, the input impedance may be increased to a sufficiently high value, even at very high radio frequencies, such as to impose low damping on the input circuit. This results in high conversion gain at these frequencies and a better signal-to-noise ratio.

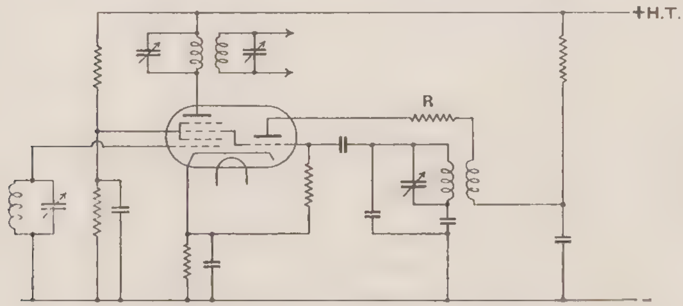


Fig. 79.—Typical circuit for triode-hexode multiple electrode valve as a frequency converter. In this system, G_1 *is the control and* G_3 *mixer grid.* R *is adjusted until constant oscillator voltage is obtained over tuning range.*

An alternative oscillator circuit, known as a *Colpitts circuit* is shown in Fig. 80 ; this circuit is preferable when oscillation at very high radio frequencies is desired, as in short wave reception over the 4 to 10 metres range. A triode-hexode of suitable design is probably

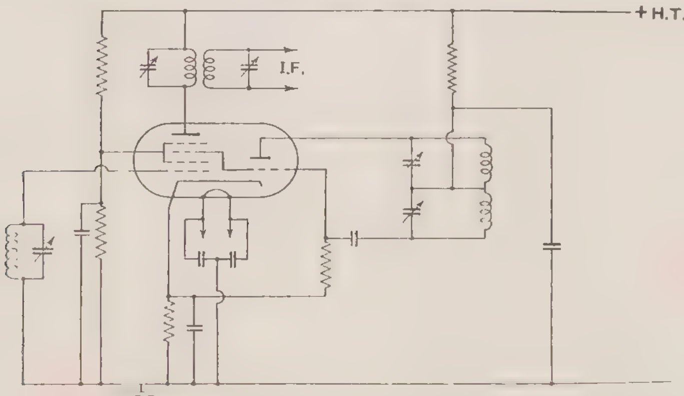


Fig. 80.—Triode-hexode as frequency converter, utilising Colpitts circuit. Suitable for ultra short wave operation. With indirectly heated valve fed by A.C. as shown, heater leads are connected through separate small capacity condensers to earth in order to prevent modulation hum.

one of the most efficient forms of frequency converter for superheterodyne receivers intended for short wave reception down to these wavelengths.

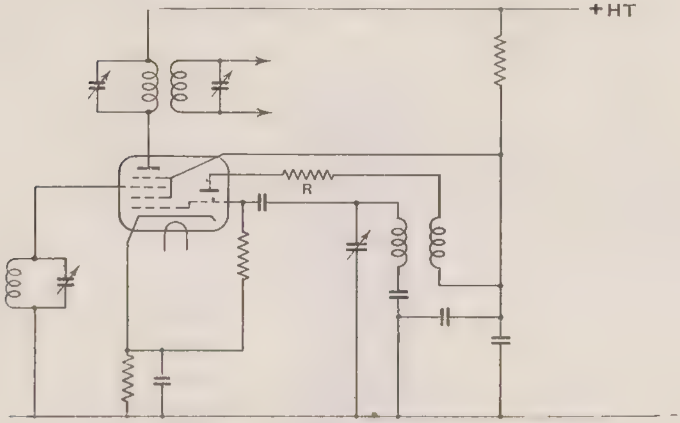


Fig. 81.—Typical circuit for triode-hexode of alternative design to that shown in Fig. 79.

An alternative construction for the *triode-hexode* is shown in Fig. 81, which has the injector grid adjacent to the cathode and the control or signal grid between the screens G_3 and G_5. The circuit diagram indicates the position of the electrodes, and the similarity between this class of valve and the two-valve arrangement shown in Fig. 77 should be noted.

Other multiple purpose valves.

Other forms of multiple valves are found in common practice, all of which involve separate cathode to anode streams in a common envelope and serve merely to combine the functions of separate electrode systems in a common envelope and on a common base. Some of the more usual types are the following:

Double diode.

This, if we include diodes suitable for power rectification, is probably one of the most widely employed multiple valves. The diodes may be designed so as to be of suitable characteristics to provide power rectification, or they may be much smaller, to provide rectification of high frequency voltages, such as in a radio frequency detector circuit.

A multiple diode valve may comprise a combination of two or three diode anodes, and may employ a common cathode, or alternatively, a separate cathode-anode system for each diode element.

Diode triode.

A combination of either a single, double or triple diode system and a triode in one envelope constitutes a diode-triode multiple valve. In all such cases the multiple valve combines rectification and amplification in the one envelope, each process being entirely separated.

The most widespread type is the double diode-triode which may be constructed either with a common cathode or on separate cathode systems for each element. The former construction is common, in which the diode anodes—requiring only a small total emission to satisfy their characteristics—are usually mounted at the end of the cathode near the electrode support " pinch."

It is usually of great importance in such valves that adequate screening against mutual interaction between diode and triode elements be provided in the design; for this reason a metallic shield is often employed and, in addition, the grid lead of the triode element is usually taken to the end of the envelope remote from the diode leads. Fig. 82 shows an electrode assembly for a double diode-triode valve, while Fig. 82(a) illustrates a typical complete valve.

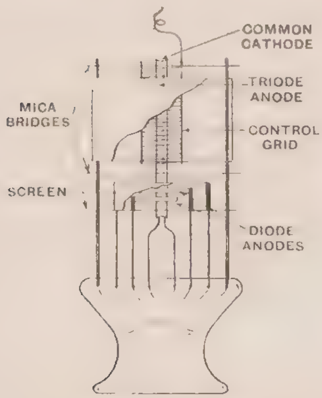


Fig. 82.—Electrode assembly for a typical double-diode triode multiple valve.

Fig. 82(a).

Fig. 82(a).—A typical indirectly heated double-diode triode —Type DH63. The triode grid is brought out to the top.

Automatic gain control " A.V.C."

Rectification of an H.F. voltage by a diode is also widely employed in automatic *gain control* circuits — commonly known as *automatic volume control (A.V.C.).* The object of automatic gain control is to adjust the sensitivity of a receiver or amplifier in such a manner that whatever may be the variation in the actual mean strength of the input voltage, the rectified output from the detector in the case of a radio receiver, or from the output valve in the case of an audio frequency amplifier, remains at a substantially constant mean value.

Fig. 83 shows a basic circuit arrangement; a diode V2 is employed to rectify an amplified H.F. voltage, the D.C. voltage developed across the diode load R_3 being applied to augment a negative bias to the grid of the amplifying valve V1. Valve V1 is self-biased by the resistance R_1, this bias being applied to its grid

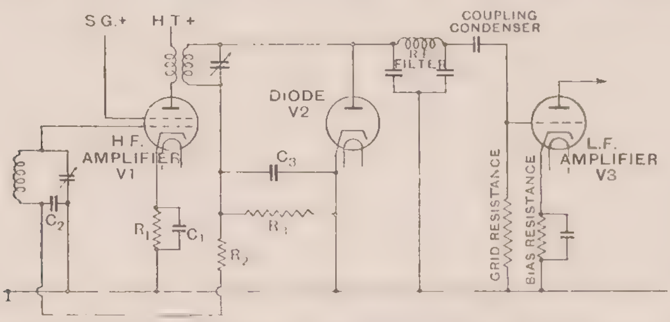


Fig. 83.—A circuit employing a diode for both detection and automatic gain control applied to a radio frequency amplifying screened tetrode. An additional low frequency amplifying triode is shown, which could be combined in the same envelope and on the cathode as V2 if desired, as a diode-triode multiple valve.

R1 *fixed bias for* V1.
R2 *decoupling for controlled valve.*
R3 *diode load.*

through the decoupling resistance R_2 and the diode resistance R_3. In the absence of a signal there is no D.C. voltage developed across R_3, but when H.F.

voltage appears across the diode, the grid of V1 becomes negative with respect to the cathode of V2 owing to the D.C. voltage now developed across R_3, and increasingly negative with respect to its own cathode, thereby reducing the mutual conductance and consequent amplification of V1.

An arrangement such as described is known as *simple A.V.C.*, and it suffers from the disadvantage that the full gain of the amplifier is lost, since even with weak signals the diode will produce *some* bias.

The disability may be overcome by biasing the A.V.C. diode negatively so that rectification will not occur until the input peak voltage exceeds this bias value. Such a system is known as *delayed A.V.C.*, and in this, separate diodes are most usefully employed for signal detection and for development of control voltage respectively. Entirely separate valves could be employed, but as the emission required and the power absorbed are very small, it is practicable and convenient to mount the diodes in a common bulb, and often on a common cathode.

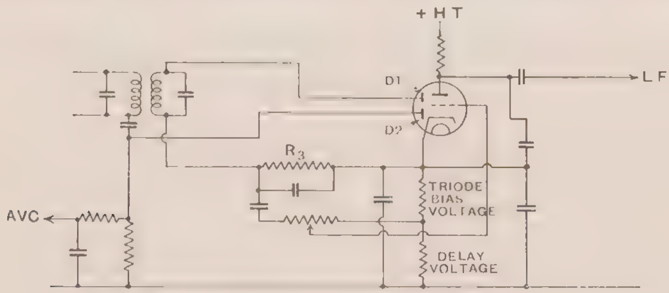


Fig. 84.—Circuit for combined double diode-triode valve, to provide detection, delayed " A.V.C." and L.F. amplification.

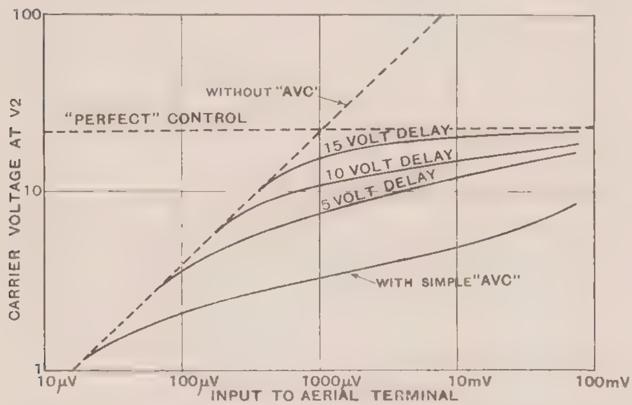


Fig. 85.—Automatic gain control curves for circuit of Fig. 84. The larger the delay voltage the flatter the control curve but the greater the detector input required.

An arrangement employing a double diode system for signal detection and delayed A.V.C. is shown in Fig. 84. In this circuit, until the peak voltage of the signal exceeds the standing voltage difference between the cathode of the double diode-triode and its A.V.C. diode D2, no negative control volts are applied to the H.F. amplifying valve, and the full amplification is therefore retained.

Fig. 85 depicts a typical A.V.C. characteristic, showing that the greater the delay voltage the more perfect becomes the control system. At the same time an

increase in delay voltage, while improving the control on a wider range of aerial input voltages, calls for greater pre-detector amplification, or the benefit of A.V.C. for weak signals will be lost.

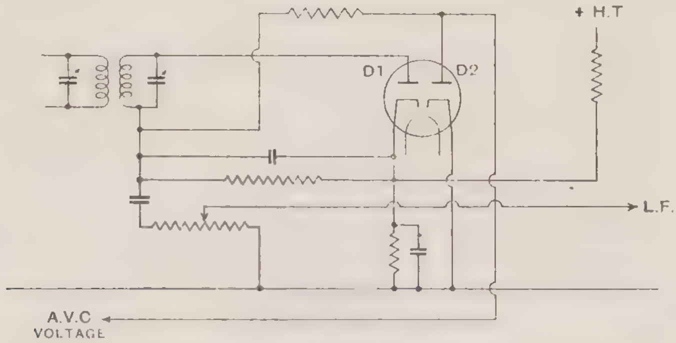


Fig. 86.—A circuit employing a double-diode valve on independent cathode systems, to provide delayed " A.V.C. " in cases where the H.T. applied voltage is limited.

Fig. 86 shows an application for double-diode valves, in cases where the available H.T. voltage is limited in value. It will be noted that the multiple valve in this case employs two separate cathodes.

Further dual system valves

Diode-tetrode and diode-pentode.

Multiple valves of these types may be designed either so that the tetrode or pentode element is fully screened and is thus suitable for high frequency voltage amplification, or partially screened and of greater power handling capacity for low frequency or power amplification. Again, the diode is shielded from the amplifying portion, and in some cases the grid and anode leads are separated in order to minimise the grid-anode capacity and reduce " feed back " at high audio, or at radio frequencies.

Double triodes and double pentodes.

In cases in which it is not essential to ensure the lowest anode-grid capacities (which would necessitate separated anode and grid lead locations) a dual triode or pentode system may be assembled in a common envelope and on a common " pinch." The normal application is in one of the push-pull circuits to be described later, and precautions are necessary in the design of these valves to ensure that there is no mutual control between the two electrode system.

When the application is in audio frequency circuits, dual triodes or pentodes are mainly employed for the sake of a possible convenience in layout and for economy reasons. It is in radio frequency amplifiers, however, particularly in short-wave applications, that the dual valve bestows more real advantages by cutting down connecting lead wires to the minimum and so reducing lead inductances and unwanted sources of coupling. In ultra-shortwave applications, the dual valve system has been extended to include valve types which embody the " ring seal " form of construction such as that used in the single H.F. pentode described, although in such cases also, careful attention to layout and wiring can avoid the necessity for the more complicated structure of a multiple system.

CHAPTER 11

Valves in Push-Pull : Valves in Parallel : " Q.P.P." : Low Impedance Loading : " Class B " Coupling Circuits : Inverse Feed-Back : Push-Pull in R.F. Circuits.

The arrangement of valves in " push-pull " has many applications in circuits both for radio frequency and audio frequency signals. When two amplifying valves are connected in a push-pull circuit, there are several essential differences in operating characteristics with corresponding effects on overall performance, and we shall now examine some reasons for employing push-pull, with methods of application.

If we want to increase the output power beyond the capacity of a single given valve, we may do this in one of three ways :

(1) By the substitution of another type of valve with greater power handling ability.
(2) By the use of two or more similar valves in parallel.
(3) By the use of a " push-pull " circuit.

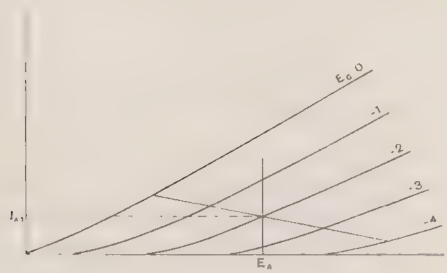


Fig. 87(*a*).—*Triode with high internal resistance (anode impedance).*

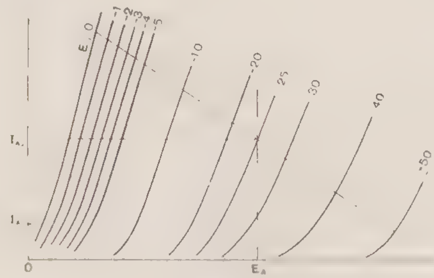


Fig. 87(*b*).—*Low resistance triode, similar mutual conductance to that of Fig.* 87(*a*).

Substitution of larger valve.

Figs. 87(a) and 87(b) indicate a family of I_A–E_A curves for typical triodes with high internal resistance and low internal resistance respectively, the curves being plotted for differences of one volt on the grid in each case. It will be seen* that, for a given anode voltage, the greater output power is delivered by the lower resistance valve, but this implies a higher standing anode current and therefore a high anode dissipation (watts loss). The power output will therefore depend upon the anode impedance (internal resistance) and the permissible anode dissipation in watts.

Comparison of parallel and push-pull arrangements.

If we connect two valves with grids and anodes in parallel, the resulting internal resistance is half that of either valve separately. The result of paralleling two similar triodes is shown in Figs. 88(a) and 88(b). In this case if the load resistance for a single valve is R_L, the sensitivity is doubled, that is, a given input grid voltage will, with load resistance equal to $\frac{R_L}{2}$, result in twice the power output of a single valve having similar characteristics. [Schematic circuit arrangements are shown in Figs. 89(a), (b) and (c). In the push-pull arrangement the valves may be represented as in Fig. 89(c), where R_L is the load resistance assumed for a single valve. Between the two anodes is a load $2R_L$, or twice that for either valve alone.]

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* From method outlined on page 47.

A comparison may now be made between the various systems :

(a) *Single valve*

The power absorbed is $I_A \times E_A$.

The grid input voltage is e_G.

(b) *Two valves of type (a) in parallel, i.e. twice the anode current for the same grid voltage, resulting in twice the sensitivity.*

The power absorbed is $2I_A \times E_A$.

The grid input voltage is still e_G.

(c) *Two valves of type (a) in "Class A" push-pull : twice the anode current for twice the input voltage.*

The power absorbed is $2I_A \times E_A$.

The grid input to each valve is e_G. But the *total* grid to grid input is $2e_G$.

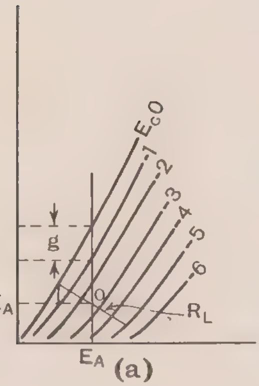

Fig. 88(*a*).

Single valve.

Anode voltage	$= E_A$
Anode current	$= I_A$
Anode dissipation	$= I_A \times E_A$ *watts*
Load resistance	$= R_L$
Grid voltage	$= E_G$
Mutual conductance between E_G0 *and* -1	$= g$
Power output (R.M.S.)	$= W_0$

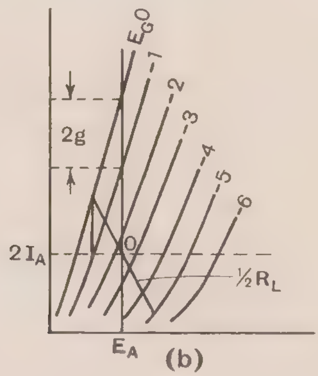

Fig. 88(*b*).

Two valves as Fig. 88(*a*) *in parallel.*

Anode voltage	$= E_A$
Anode current	$= 2I_A$
Anode dissipation	$= 2I_A \times E_A$ *watts*
Anode resistance	$= \frac{1}{2}R_L$
Grid voltage	$= E_G$
Mutual conductance between E_g0 *and* -1	$= g$
Power output (R.M.S.)	$= 2W_0$

It follows from the analysis above that with correct anode loading, the sensitivity of the push-pull circuit is equal to that for the single valve, assuming each valve operates under the same conditions of anode current and grid input as for a single valve. In a push-pull amplifier, therefore, while the power output may be doubled under suitable conditions, the *total* input voltage must also be doubled to obtain this benefit, whereas in the case of paralleled valves the power output is doubled without the necessity for doubling the input voltage.

Even though the sensitivity of the push-pull arrangement is lower than that of the parallel arrangement, it is often preferred, for the following reasons :

(1) With push-pull, a large steady current flowing through the anode load may be avoided, and if the load consists of an iron-cored inductance a smaller core may be employed.

(2) In a push-pull circuit, introduction of second harmonics (and other *even* harmonics) caused by curvature in the valve characteristics may be greatly diminished, as the *even* harmonics generated tend to cancel out in operation.

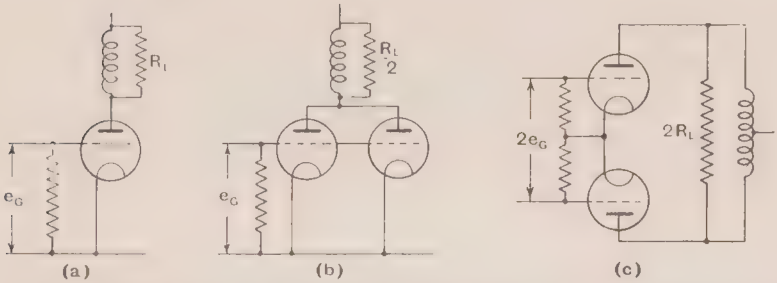

Fig. 89.—Schematic diagram of push-pull arrangement (c) in comparison with single (a) and parallel (b) valve systems.

(3) Stability is improved by reduction in the alternating current flowing through the common H.T. source of supply.

(4) In radio frequency circuits the possibility of reduction in the effects of inter-electrode capacity becomes of importance, particularly in short wave applications.

From the fundamental principle we can now proceed to more particular applications of amplifying valves in push-pull circuits. Fig. 90 shows the fundamental circuit for a push-pull amplifier. (Applicable to H.F. or L.F. circuits.)

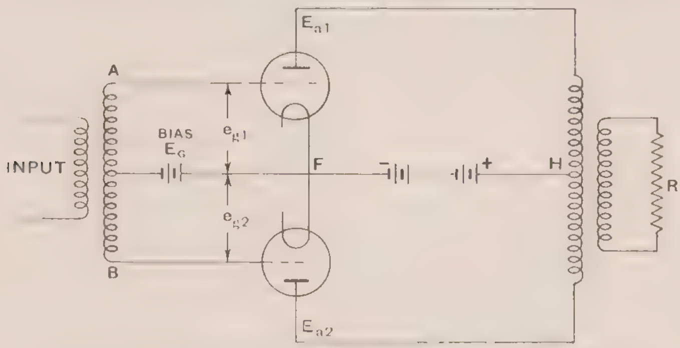

Fig. 90.—Fundamental arrangement of push-pull amplifier.

" Class A " push-pull

This system consists in so operating the valves that the grid biasing voltage is substantially the same as for a single similar valve in " Class A " ; that is, that the mean anode current for each valve is independent of the alternating component of the grid voltage, and for our purpose at present there is also absence of positive grid current. In this case each valve acts as a separate linear amplifier.

We have seen that the anode load resistance for greatest undistorted power is in this case twice the value for a single similar valve of the push-pull pair, and the combined output is double that for a single valve, provided that the input is also doubled. In " Class A " push-pull, the mean anode to cathode current remains substantially constant in operation, and thus the negative grid bias voltage for the valves may be provided by means of the voltage drop across a series

cathode resistance, giving "automatic" or "free" grid bias. This simplifies the biasing arrangements and compensates for imperfectly regulated H.T. power supply, so avoiding loss in output power which might otherwise result from fluctuating H.T. voltages.

Due to the comparative simplicity and economy of the associated circuits required for amplification without excessive harmonic content, "Class A" push-pull is often preferred. However, in this arrangement the total power loss (anode dissipation) is continuous, whether the signal voltage is applied or not, and is double that for a single similar valve. No great advantage in efficiency of power conversion is obtained over that for a single valve, and modifications in operating conditions, such as we shall now examine, are often employed to increase this efficiency.

"Class B" push-pull

When a valve is used in "Class B" push-pull its mean grid voltage occurs at a point approaching the "cut-off" of anode current; it is here that the full benefits of the increased efficiency possible with push-pull circuits are realised.

A single valve under such conditions would result in almost complete suppression of the negative half-cycle of anode current, and almost perfect rectification; in other words, a large second harmonic component would appear. Two valves so operated can, however, be used in a push-pull circuit, such that one valve functions as an amplifier on the positive half cycle of input voltage, and the other on the negative half cycle. The A.C. components of the anode current are then combined in the anode load.

The essential difference from "Class A" is therefore that the anode current can vary from very small to very considerable values, and the *average* anode current will depend on the signal voltage. This is the fundamental feature of "Class B" operation and it follows that in such a condition the power drawn from the H.T. source is dependent upon the value of applied signal voltage.

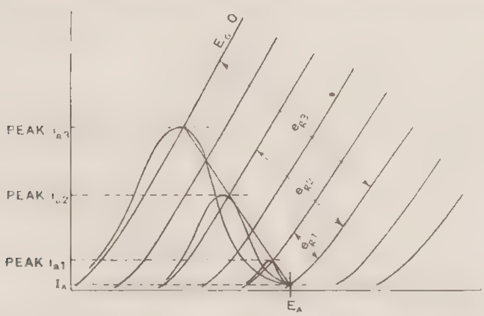

Fig. 91.—*Anode current waveform superimposed upon* I_A–E_A *curves of triode, operating under "Class B" conditions.*

Fig. 91 indicates clearly that, in a "Class B" biased condition, the peaks of anode current taken by a given triode depend upon the value of signal voltage e_g impressed on the grid. Owing to this, it is essential that the "regulation" of the anode supply should be good; that is, that the H.T. supply must have low internal resistance, and the grid bias voltage should be obtained from a fixed source independent of the cathode current.

The application of the "Class B" push-pull condition varies according to the characteristics of the valves, and the requirements of the circuit, and these we shall now review briefly.

"Class B" in which the grid is not driven positive

In the curves of a low internal resistance triode, such as shown in Fig. 92, the "Class B" condition is represented by an operating point of grid bias voltage such as at X. Two considerations resulting from this choice of operating anode current are apparent:

(a) The standing anode current is less than that for normally biased "Class A," and the average anode current will depend upon the signal

voltage, increasing as the grid input is increased. The effect becomes more marked as the "cut-off" point of I_A is approached.

(b) The power output may be greatly increased by decreasing the value of the load impedance. There are two limits to the increase in power in this way: when the peak anode current reaches the maximum obtainable from the cathode emission, or when the anode dissipation reaches the maximum permissible value.

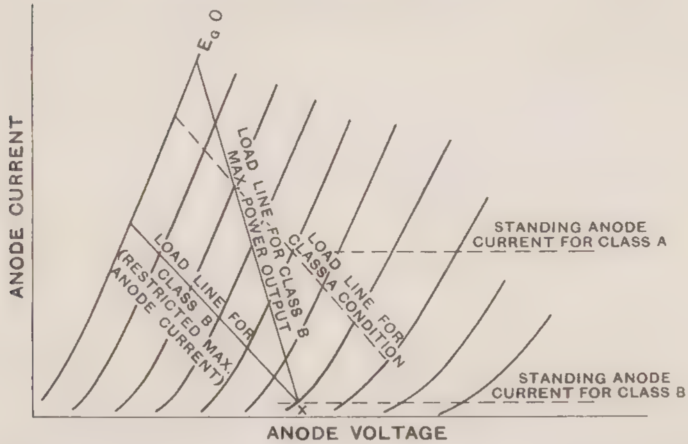

Fig. 92.—Comparison between "Class A" and two alternative applications of "Class B," the one alternative for maximum economy in average anode current (Q.P.P.) and the other alternative for maximum power output (low impedance loading).

It will be seen, therefore, that these operating conditions can be applied in either of two ways:

(a) *To economy in current drawn from the H.T. source.*

This is achieved by fixing the negative grid bias such that with no signal the anode draws very little current and the anode currents vanish for almost a complete half cycle in each valve in turn. This method is commonly known as *quiescent push-pull* (*Q.P.P.*), and is particularly applicable to battery operated triode or pentode valves, where an economy in H.T. current is important.

(b) *To increase in power output.*

This is achieved by so constructing the valves that the cathode emission of each is adequate to satisfy a large peak anode current, and if triodes, they are designed to have a very low internal resistance. This permits a considerable reduction in anode load impedance which in turn results in a substantial increase in maximum anode power. In this application there is not the same interest in anode current economy, and the method is sometimes known as *low impedance loading push-pull*, or "Class AB1."

Positive drive "Class B."

Hitherto we have looked only at conditions of amplification which do not intentionally introduce positive grid current. Any grid current resulting from excessive peak grid voltage would, with components designed for "Class A" or

"Class AB1" operating conditions, introduce a distorted output waveform and reduced power. We now come to a consideration of systems in which the peak grid voltage is allowed to cause the grid to take up a positive potential, with consequent introduction of grid current and the expenditure of power in the input circuit.

The essential difference in operating conditions and associated components between the positive drive case and the "Class AB1" or "Class A" cases lies in the input circuit, which has now to provide power. This is normally achieved by means

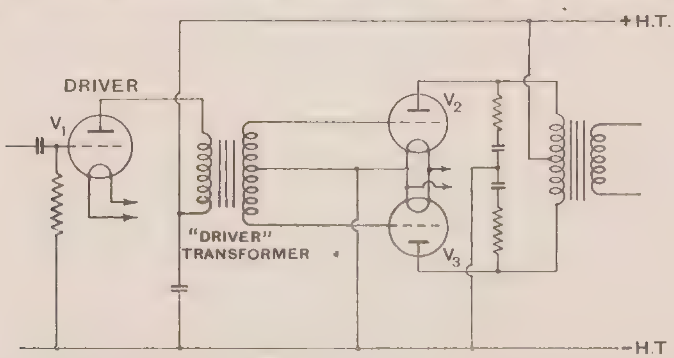

Fig. 93.—Typical circuit for "positive grid drive" showing driver stage.

of a "driver" stage of power amplification, and a typical circuit for an audio frequency arrangement is shown in Fig. 93. Here V_2 and V_3 are the output valves operating in a positive drive "Class B" push-pull circuit, and V_1 is the "driver" valve.

Positive drive "Class B" push-pull amplifiers are capable of a much higher ratio of output power to power loss (continuous anode dissipation) and therefore represent a great increase in power efficiency over "Class A" arrangements. The high peak values of anode and grid currents, however, call for special precautions in the manufacture of the valves to ensure adequate cathode emission and degassing of the electrodes. The increased efficiency of the amplifier is often offset by the increased cost of the driver components, and in an audio frequency amplifier it is essential for the driver transformer to be constructed with a low leakage inductance.

Valves for positive drive "Class B" can be divided into two main classes :

(1) Those in which a "cut off" in anode current occurs at or about zero grid voltage. The characteristic curves of a triode so designed are

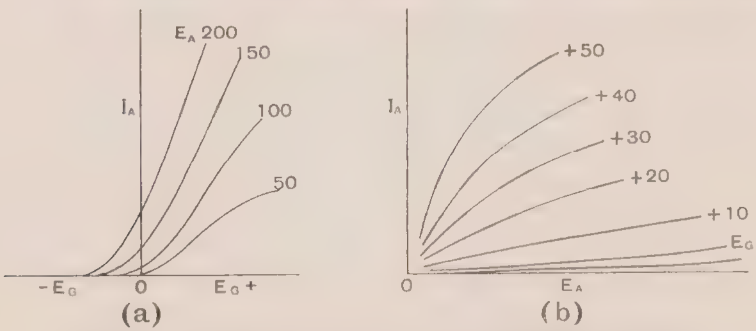

Fig. 94.—I_A–E_G and I_A–E_A curves for triode designed to operate at approximately zero grid bias.

shown in Figs. 94(a) and 94(b). From these it will be seen that the I_A-E_A curves take up a form similar to that for a pentode.

Such a valve has a closely wound grid, giving a high "m" or or amplification factor. The method, known as *zero bias "Class B,"* has the advantage that no special grid bias arrangements are necessary.

(2) Those which normally operate with the grid negatively biased. Such an arrangement is similar to "Class AB1" for moderately low input grid voltages, in which the valve operates without grid current, but above a given input, the grids are driven positive and the conditions become those of the positive drive amplifier which we have already considered. This method is sometimes called "*Class AB2*," and if the increased cost of the associated driver stage can be allowed for, is often preferred owing to the increased efficiency as compared with "Class AB1".

The main disadvantage of "Class AB2" is the need for a bias unit which can take the positive-grid current without altering its voltage.

Cathode loading.

In positive drive "Class B" amplifiers, use may be made of the method of cathode loading of the driver valve and direct coupling to the push-pull grids, as shown in Fig. 95. This is advantageous owing to the means it affords of maintaining a low impedance in the driver stage. By placing the driver load in the cathode circuit, the voltage developed in the load is allowed to be "fed back" into the grid circuit and so reduces the output impedance of this stage.

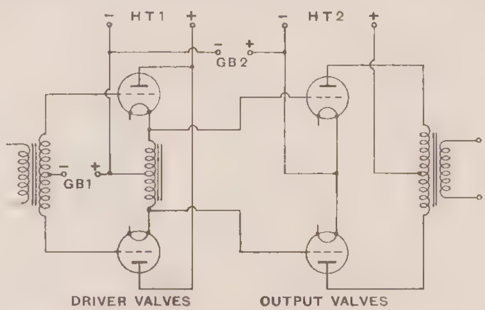

Fig. 95.—Circuit for cathode loading of driver valves, for positive grid drive "Class B" output stage.

Inverse feed-back.

Degeneration, inverse feed-back, or *negative feed-back* as it is variously called, is a means of increasing stability of amplification despite changes in circuit constants, and may be applied to reduce amplitude distortion.

There are two methods of applying feed-back to an amplifier—one which tends to maintain a constant output current, and the other a constant output voltage.

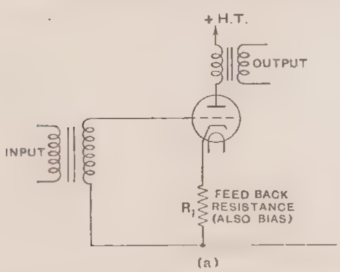

Fig. 96(a).—Feed-back circuit for increasing the output resistance. The feed-back resistance also provides grid bias.

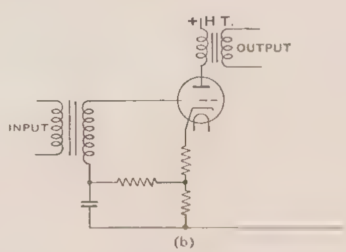

Fig. 96(b).—Feed-back circuit which gives an output resistance higher than the valve resistance, and in which a greater amount of feed-back than the bias resistance provides, is allowed for.

The former results in an increase and the latter in a reduction in the output impedance of the amplifier.

Consider now the two general aspects of applying inverse feed-back :

(1) *An arrangement which derives its feed-back voltage from a circuit in series with the output, resulting in an output resistance higher than the valve resistance.*

Such a circuit is indicated in Figs. 96(a) and 96(b) on page 79. This application of feed-back is useful in relation to the use of filter networks in which a correctly designed electrical filter is required, terminating at each end with a resistance equal to its characteristic impedance. If a valve is employed as a termination the filter is only correctly terminated when the valve is of the same effective resistance, which can be achieved by the use of feed-back in this manner.

(2) *An arrangement in which the feed-back voltage is derived from a circuit in parallel with the output, resulting in an output resistance lower than the valve resistance.*

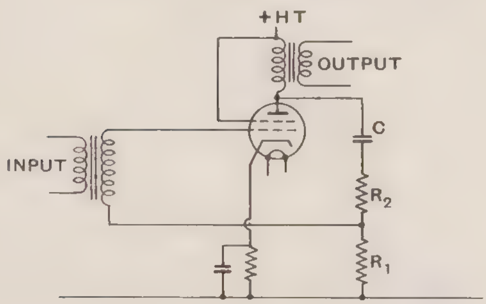

Fig. 97.—Feed-back circuit for reduced output resistance.

Such a circuit is indicated in Fig. 97. This application may be employed to considerable advantage where a tetrode or pentode is used, and is effective in " damping out " resonant peaks and reducing causes of distortion or excessive peak voltages across the load.

The feed-back network can be made to have the same transmission loss characteristic as the desired gain characteristic, and distortion in an amplifier can be to a great extent cancelled out.

Inverse feed-back, or degeneration, is introduced by superimposing upon the amplifier input a contrary voltage derived from the output circuit so that the actual input to the grid consists of the signal voltage minus the feed-back voltage. The effective gain is reduced by the presence of inverse feed-back.

Push-pull applied especially to radio frequency circuits.

Consideration has already been given to the triode as a generator of oscillations, and the application of two similar valves in a push-pull circuit follows simply from the explanations already given of the push-pull amplifier and of the oscillation generator. A circuit suitable for regeneration, or production of an oscillatory current, is shown in Fig. 98 ; a tuned circuit is connected between the anodes of the two valves, and the middle point of the tuned circuit inductance is common with the cathodes.

The advantage of the push-pull circuit for radio frequency oscillators is that it helps in avoiding unbalanced stray capacities. The use of *balanced lines* instead of tuned circuits in short wave oscillators accounts for its widespread use. Fig. 99 shows a double-triode valve suitable for push-pull operation in either radio or audio frequency amplifiers.

In radio frequency amplifiers, the push-pull arrangement also lends itself readily to the use of neutralising condensers for balancing inter-electrode capacitive coupling (Fig. 100). The neutralising condensers are connected between the anode

of one valve and the grid of the other. This system combines the advantages of centre taps on both input and output circuits, which could only be obtained separately in a single neutralised valve.

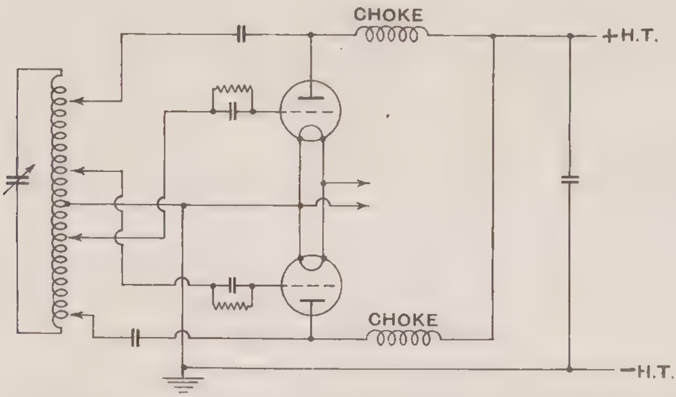

Fig. 98.—Push-pull circuit for generation of H.F. oscillation.

"Class C" push-pull.

In radio frequency push-pull circuits a form of operation known as "Class C" is often utilised. The "Class C" amplifier normally operates with a mean grid biasing voltage such that anode current flows during only a fraction of the positive excitation cycle of signal input voltage; the negative grid polarising voltage is normally fixed at somewhat greater than twice the value required for anode current "cut-off" without grid excitation.

Fig. 99.—A typical double triode designed for push-pull operation, either for radio or audio frequencies—Type DET19.

The main characteristic of a "Class C" amplifier is high power conversion efficiency. This form of circuit lends itself particularly to a radio frequency power amplifier whose output is required to be modulated up to 100% by a separate modulating source of power. This condition implies that the modulated R.F. amplifier should operate with a steady D.C. power input equal to twice the modulator's maximum undistorted power output, and should at the same time offer a load to the modulator equal to its optimum load resistance. "Class C" is only suitable for radio frequency amplifiers and has no application for audio frequencies.

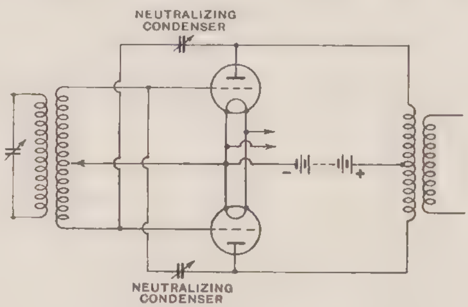

Fig. 100.—Push-pull H.F. circuit showing neutralising condensers.

CHAPTER 12

Gasfilled Valves : Mercury Vapour Rectifiers : Gasfilled Relays.

So far in this review we have been studying only high vacuum valves, that is, valves in which the evacuation process has been so thoroughly carried out in manufacture that the number of molecules of air or gas remaining within the bulb is so small that danger of electron collision and release of positive " ions " from the remaining gas can for all practical purposes be neglected. These are called " hard " valves.

In the following pages we shall examine the principal differences in properties and application between " hard " valves and " gasfilled " valves—the latter containing sufficient molecules of a gas or vapour to have appreciable effect upon the character of conduction through the valve. A very small trace of certain gases or vapours within a valve is often harmful in its effects even though the number of gas molecules is too few, or the electrode voltages too low, to cause " ionisation " of the molecules. When the amount of gas is sufficient appreciably to affect the conduction characteristic, the valve is called " soft."

Soft valves operating with no appreciable ionisation, have been employed as detectors or rectifiers of radio frequency signals, but owing to the critical nature of the adjustment, and the dependence on temperature, cathode surface material and individual characteristics, the unreliability of this method in practice outweighs its utility.

This chapter, however, is mainly intended to deal with gas- or vapour-filled valves, working at voltages at which considerable ionisation occurs, and in which the gas or vapour is deliberately introduced, and the design so chosen that the valve can operate in this condition without harm.

The nature of the gas or vapour present within the envelope is important in its effect on the operation ; for instance, oxygen or water vapour are particularly destructive to the emissive properties of dull-emitter cathode surfaces. On the other hand, mercury vapour and the inert gases such as helium, argon and neon, do not react in this way on the cathode emission.

Operation of a gasfilled valve.

Let us examine the principles of operation of a gasfilled valve. On heating the cathode to the temperature required for electron emission, and on applying a low positive voltage to the anode, a small anode current passes, limited by the internal resistance, which is now comparable to that of a similar hard vacuum valve at very low anode voltages. Immediately the positive anode voltage is increased to a certain voltage (in the neighbourhood of 15 volts), the whole action of the valve is changed. At this voltage a much larger current, equal to the full saturated current, will now flow owing to ionisation of the gas molecules by electron bombardment, the positive ions thus released going to neutralise the space charge. Since the positive ion is much heavier than the electron, it traverses the valve more slowly and therefore during the time that one positive ion is travelling from anode to cathode, a large number of electrons can pass from cathode to anode.

To produce complete neutralisation of the space charge, it is only necessary for one electron in about 600 to collide and produce a positive ion. On the other hand, the amount of current carried by the gas ions will be very small compared with the electron current, and therefore the maximum current the valve will carry is the full thermionic emission of the cathode.

There are two essentially different classes of gasfilled valves—the one which has already been described, and a second class in which a large increase in current

capacity is obtained due to the "blanketing" effect of high gas pressure, which prevents loss of active material from the cathode and permits higher cathode temperatures. This second class contains inert gas at a higher pressure, and has the property of permitting larger anode currents—of the order of several amperes—without the necessity for higher cathode wattages; it is, however, limited in the reverse voltage it will stand. The high gas pressure class of valve is normally restricted in reverse voltage to about 300 volts, and is commonly employed for rectifier circuits (such as for battery charging) requiring several amperes of rectified current, but at low voltages of the order of 12 to 30 volts only. The high pressure class usually employs an inert gas such as argon, whereas the low pressure class normally makes use of mercury vapour.

The use of a low pressure gas instead of a vacuum also introduces the possibility of using devices to increase the efficiency of the cathode. An example arranged for direct heating is shown in Fig. 101. This is the mercury-vapour GU50 rectifier, in which the directly heated oxide-coated strip filament is bent into a zig-zag formation. Directly heated cathodes of this general form have a much higher thermal efficiency than those in vacuum valves.

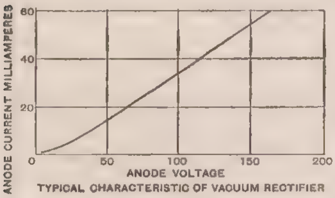

Fig. 102.—Typical characteristics of vacuum rectifier.

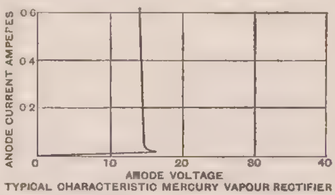

Fig. 103.—Typical characteristics of mercury vapour rectifier.

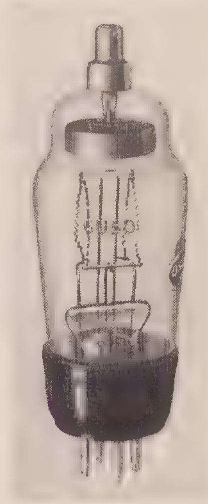

Fig. 101.—A typical mercury vapour filled rectifier for half-wave rectification — Type GU50.

Gasfilled rectifiers.

One of the difficulties associated with the use of hard valves as power rectifiers is their relatively high internal impedance as compared with the load circuit. This internal impedance may be reduced by employing cathodes of large emissive surface area, and by reducing the cathode-anode mechanical clearance to a limit set by structural considerations. A relatively high rectifier impedance also causes poor "regulation," in other words, the rectified voltage becomes largely dependent upon the rectified current drawn from the valve.

In a gasfilled valve the positive ions neutralise part of the negative space charge, which in a vacuum rectifier limits the anode current; this neutralisation of the space charge is the factor which gives to the gasfilled valve its valuable property of low internal resistance.

In a mercury vapour, or gasfilled rectifier, once the ionisation voltage has been attained, the discharge may be maintained with a voltage drop of only about 15 volts across the valve, but in this condition the current to the anode may rise to the full value permitted by the available cathode emission. There is thus only a small resistance to be overcome in the valve itself, and practically the whole of the total emission is available for feeding into the load; in other words, the voltage dropped across the valve is practically independent of the current through it and due to this feature, very high efficiency may be realised. Figs. 102 and 103 indicate typical characteristics of the high vacuum and mercury vapour rectifiers respectively.

Precautions when using gasfilled rectifiers.

When using a mercury vapour or gasfilled rectifier, several important precautions in use must always be borne in mind.

1. *Delayed switching.*

In a mercury vapour valve it is essential for the voltage drop across the valve to be lower than a certain critical value, or destruction of the cathode as a low temperature emitter will occur.

This means that time must elapse to allow adequate cathode emission before either the anode voltage is applied, or an external load circuit is connected. (In some cases a limited current may be drawn from the rectifier until such time as its cathode is fully emitting, but this procedure is not always satisfactory.)

In the mercury vapour type of valve, metallic mercury is inserted into the envelope and some of this vaporises when the cathode is heated. It is important for adequate heating time to be allowed to vaporise any mercury which may have distilled on to the walls of the envelope, or which might in the liquid state lead to a short circuit between anode and cathode. In addition, back bombardment by heavy ions on to the cathode is liable to cause rapid disintegration of the cathode surface.

2. *Maintenance of cathode temperature.*

For the same reasons as given above, it is important that the operating cathode temperature be maintained at a given figure for the emission required and, particularly in cases of large load currents, close regulation of filament voltage becomes necessary, and this must never fall below the manufacturer's minimum value. This implies that the control of rectified voltage should be made only by control of applied anode voltage, or alternatively in the output circuit by a potentiometer or series resistance, this precaution being even more essential than in the case of hard vacuum rectifiers. The condition also implies that when switching off the supply, arrangements should be made for the anode voltage to be removed simultaneously or slightly earlier than the cathode voltage.

3. *The nature of the load.*

We have already seen (chapter 3) the effect of a condenser load upon a rectifier. In the case of mercury vapour and gasfilled rectifiers a high capacity condenser across the valve imposes a heavy peak current load, and in certain cases may result in cathode disintegration. It is therefore desirable in such cases to feed the output current through a series resistance or choke which will serve to limit the current and minimise danger of breakdown by back bombardment.

A typical circuit is that shown in Fig. 104, in which two half-wave gasfilled rectifiers are employed to provide biphase rectification, the output being taken through an inductance L, before applying it to a condenser filter circuit. This precaution is of particular importance if the maximum rectified current of which the cathode emission is capable is to be drawn from the valve. It is also desirable to ensure that the smoothing circuit does not resonate to the supply frequency.

4. *The "ambient" temperature.*

In large rectifiers of the mercury vapour type, the temperature

of the air immediately surrounding the envelope (the "ambient" temperature) must be controlled. Too high an ambient temperature, such as would result from operation of the valve in a confined space, will cause the anode and the envelope to overheat, which may result in a "back-fire"; too low an ambient temperature, such as resulting from draughts of cold air, will cause condensation of the mercury vapour on the walls of the envelope, and consequent danger

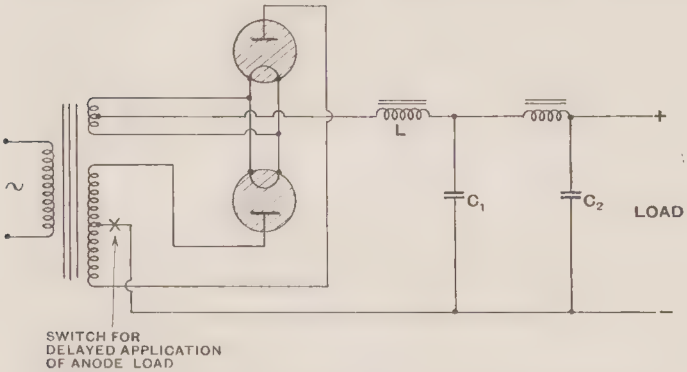

Fig. 104.—*Two half-wave gasfilled rectifiers in a biphase half-wave circuit with choke input filter.*

of back bombardment, or even electrode short circuits by metallic mercury. The actual ambient temperatures required depend on the type of valve, but may vary from about 10°C. to 40°C.

Gasfilled controlled diodes (gasfilled triodes).

These are known variously as *gasfilled relays*, "*Thyratrons*," *grid glow tubes*, etc., and the fundamental principles of such thermionic devices and some of their applications are of considerable importance.

We have seen what are the essential differences in operation between a hard vacuum diode and one containing gas or vapour under ionisation conditions. Thus at low voltages, below that of ionisation, the internal resistance is high and the anode current is limited by the space charge, as in the case of vacuum valves. In this condition the introduction of a control electrode, or grid, will operate on the anode current to affect the quantity of electrons flowing to the anode. This will take place according to the grid potential, as in a simple triode valve, providing the grid is maintained at a sufficiently large negative potential to be below the ionisation potential of the gas. In the state of ionisation, however, the grid will not be able to exercise any control of the anode current. This is because the grid becomes surrounded by a sheath of positive ions whenever a negative grid voltage is applied, and this "sheath" insulates it and prevents it from exerting any controlling field on the anode current. Because of this sheath of positive ions, even a very large negative grid potential will have no appreciable effect on the anode current, *which can now be controlled only by the external circuit.*

The value of the anode voltage at which the discharge will start depends on the grid potential. Thus the grid may be utilised to start the anode current at any desired anode voltage above the ionisation potential, but after that, it ceases to take any further part in the action of the device until the positive anode voltage is removed.

The value of anode potential at which the ionisation takes place is critical and depends on the grid potential, and also on other conditions, such as the gas pressure. The ratio $\frac{\textit{anode potential}}{\textit{grid potential}}$ at the critical striking point of the discharge is known as

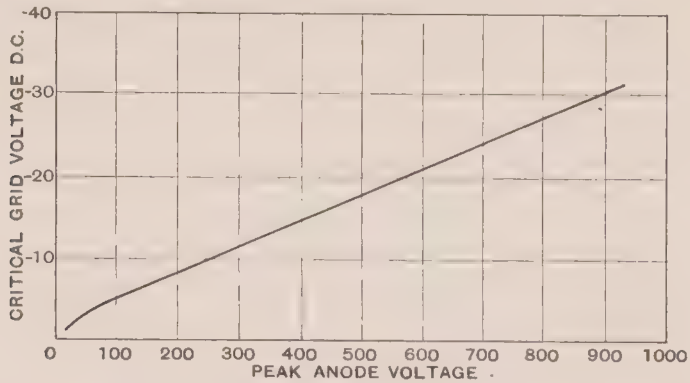

Fig. 105.—*Gasfilled relay grid control characteristic.*

the *grid control ratio.* Thus, for each value of anode voltage there is some value of grid voltage which will prevent the discharge. If the grid is less negative than this critical value the discharge will take place. A typical grid control characteristic for a gasfilled relay is shown in Fig. 105.

Fig. 106.—*A typical gasfilled relay with argon filling, designed for a maximum controlled current of* 1.0 *amp. peak or* 0.3 *amp. average—Type GT1C.*

The grid current before ionisation occurs consists of a flow of electrons to the grid, and is very small, but when the discharge commences the grid current can rise very considerably and consist of a positive ion current to the grid if the grid is negative. Should the grid become sufficiently positive for it to attain the ionising potential, an arc discharge to the grid will occur unless some precaution is taken to limit the current, and for this reason a high resistance is usually connected in series with the grid.

The only satisfactory method of stopping the discharge is to reduce the anode voltage to a value below ionising potential for a period long enough to allow recombination of the ions, as the grid cannot control the starting of the discharge if positive ions are still present. This time for recombination, known as the *de-ionisation time,* is in many applications an important characteristic of the gasfilled relay; its value may lie between 10 and 1000 micro-seconds, according to the design of the relay, and the conditions under which it is operated.

The gasfilling may be mercury vapour, but in many cases one of the inert gases is used, such as argon, helium or neon. The use of an inert gas, such as argon, is often advantageous in reducing the temperature coefficient, that is, in making the operation of the device more independent of fluctuations in ambient temperature. For this reason, argon-filled relays are normally preferred for applications where consistency and repetition are essential, such as in laboratory measurements, etc. In general, the mercury vapour types are more applicable to cases where higher voltages are necessary, as in industrial work. A typical argon-filled relay, type GT1C, is illustrated in Fig. 106.

Application of the gasfilled relay.

The applications of a gasfilled relay are so many and varied that they cannot be entered into in full detail here. The effects of control with direct and alternating voltages applied to either grid or anode can, however, be usefully summarised as below:

1. *With D.C. anode feed and D.C. grid control.*

   This is the simplest case in which the removal of a negative polarising voltage on the grid starts up the ionisation and causes anode current to flow when the grid voltage passes the critical value; the valve then operates as a simple thermionic relay. In this case the anode current can only be stopped by breaking the anode circuit.

2. *With D.C. anode feed and A.C. grid control.*

   The case is similar to (1) except that the anode current can be caused to flow as the applied A.C. grid voltage is increased and its peak value passes the critical voltage; the extent of applied grid voltage to cause the discharge depends on the initial fixed negative bias. Once again the anode current can only be stopped by breaking the anode circuit, and once the discharge is started the grid exercises no further control.

3. *With A.C. anode feed and D.C. grid control.*

   Unidirectional pulses of anode current corresponding to each positive half-cycle are obtained, of amplitude depending upon the extent of negative bias applied to the grid, so that if the grid is at cathode potential the full positive half-cycle of anode current flows, which is consistently reduced as the negative grid bias is increased until the grid voltage attains the " critical " value, sufficient to withhold the discharge, when the anode current is *halved* on the positive half cycle. At bias voltages beyond the point, the discharge is entirely prevented and no current flows. In this case the valve is " reset " to the non-conducting condition each time the anode voltage reverses in phase. This condition has an advantage over (1) in that it is a " resetting " relay.

4. *With A.C. anode feed, and A.C. grid control.*

   In this case the phase difference between anode and grid voltages is the controlling factor. If by means of a suitable phase-shifting circuit, the phase of the grid voltage can be caused to be advanced from 180° out of phase to a condition of " in phase " with the anode voltage, the anode current will simultaneously change from zero to the *full* value of the positive half-cycle. If the grid is maintained 180° out of phase and its voltage progressively decreased from some negative value, there will be zero anode current until the grid voltage passes the critical figure, at which point the anode current immediately rises to its full value.

An application of the gasfilled relay of practical importance in our present survey will be referred to in chapter 14 under the heading, Time-Base Circuits for Cathode Ray Tubes.

Precautions when using gasfilled relays.

The precautions in use already described for mercury rectifiers apply also to gasfilled relays, and should be carefully observed to ensure reasonably long life. In

addition, with mercury vapour relays, it is often the case that deterioration will occur on standing idle and for this reason it is desirable to put the relay into operation at frequent intervals, or alternatively, to store with the cathode at working temperature.

CHAPTER 13

ELECTRON BEAMS : THE CATHODE RAY TUBE : VACUUM TUBES : GASFILLED TUBES : FOCUSING : DEFLECTION METHODS.

Hitherto we have considered the operation of a thermionic amplifying valve as depending fundamentally on the *intensity* modulation of the cathode emission by means of a control grid or grids. In this method of operation the anode current is increased or reduced by varying the voltages applied to the control electrodes.

An alternative method of controlling the quantity of electrons arriving at the anode is to utilise the principle of *deflection* modulation of the cathode emission. This usually involves first the formation of an *electron beam* whereby the electrons emitted from the cathode are concentrated into a limited area or beam, which can be placed under the influence of electric or magnetic fields, or a combination of both. These electric or magnetic fields may be controlled by the voltages to be amplified, and finally the electron beam may be directed against a positive plate or anode.

The first essential in this method is to produce the electron beam, and to this end some " focusing " device must be brought into operation. In general there are two main methods by which a beam of electrons may be focused on to a given point ; the one is employed with a hard vacuum and makes use of an arrangement of electrodes with suitable voltages and dispositions in the electron stream,* and the other makes use of the presence of gas in the bulb. The principle of the deflection controlled valve has, at the time of writing, not attained widespread commercial significance, although practical valves have been produced which are designed to operate as " beam valves."†

Essentials in a cathode ray tube.

It is in the *cathode ray tube* that deflection control of an electron beam has been developed to the most practical degree, and in which this finds its widest application at present. The cathode ray tube is an electron device in which, by electron bombardment of a fluorescent screen of suitable design, changes in direction or intensity, or both, of an electron beam may be visibly observed.

There are five essentials in such a device :—

(1) The source of electron emission.
(2) The " accelerator " or " anode."
(3) The " focusing " system.
(4) The fluorescent screen.
(5) The deflection system.

In addition, the electron beam may also be intensity controlled by means of a suitable modulating electrode. A large degree of cathode emission is not normally

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*Using the principles of " Electron Optics."

†" Beam " valves, as dealt with here, must not be confused with so-called " beam tetrodes " (already described in chapter 9) in which intensity control is still utilised, although the electrodes may have some focusing effect on the electron stream.

called for, as the tube is not required to develop power, but it must withstand voltages large enough to accelerate the electron emission sufficiently to produce a clearly visible fluorescence on the screen. The cathode may be either of the directly heated filament, or indirectly heated type, depending to some extent on the class of tube and function.

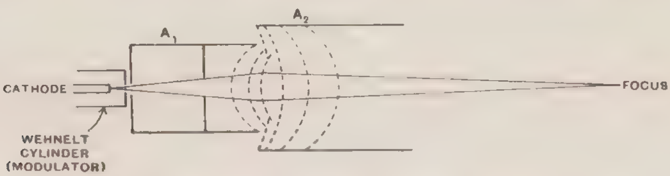
The most important problem connected with cathode ray tube design is probably that of finding methods for producing from the divergent cathode emission an electron beam which may be converged to a focus on the fluorescent screen. Since electrons are emitted in a random manner from the cathode, the resulting emission from it is a divergent beam, which divergence is further increased by the natural repulsion of the electrons. This divergent beam must be changed to a convergent one and furthermore, must be focused at a plane exactly corresponding to the plane of the screen.

Three methods are available for focusing the cathode rays :

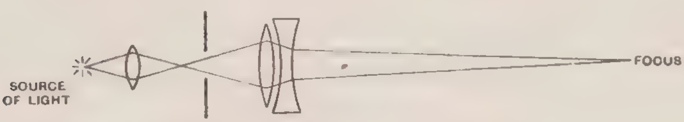
(1) Electrostatic focusing.
(2) Electromagnetic focusing.
(3) Gas focusing.

High vacuum tubes—electrostatic focusing.

This system makes use of what we may call an "electron lens." Fig. 107 represents diagrammatically the usual arrangement of an electrostatic electron lens. The electron stream emerging from the cathode is divergent, and may first be controlled in intensity by a concentric cylinder (the "Wehnelt" cylinder) to which varying values of negative voltage can be applied, as in the case of the control grid



Illustrating electrostatic focusing in vacuum cathode ray tube.



Optical analogy of electrostatic focusing.

Fig. 107.

of a valve. The divergent electron stream is made to pass through a small aperture in a cylindrical electrode A_1 at a positive potential and further on in its passage, to pass through a second cylindrical electrode A_2 normally at a higher positive potential than A_1. This second electrode A_2 may be the "anode" of the tube. The difference of potential between A_1 and A_2 produces an electrostatic field shown by the dotted lines in the figure, which operates on the electron beam in the same manner as a convex lens on a beam of light, changing the diverging beam of electrons into a converging beam.

The "focal length" of the electron lens may be varied by altering the ratio between the voltages applied to A_1 and A_2. Thus, if the voltage of A_1 is too high, the beam will be too divergent ; if too low, the focal point will recede from the

screen towards A_2, and at the same time the diameter of the beam at the new focal point will be decreased.

In many ways the electron beam is analogous to a light beam, but an essential difference lies in the fact that, unlike a light beam, the electrons comprising the cathode ray beam carry negative charges and thus mutually repel each other. For this reason the "spread" of electrons at the focal point increases with the beam current, but the spot size at the focal point can be reduced (for a given beam current) by an increase in the anode voltage.

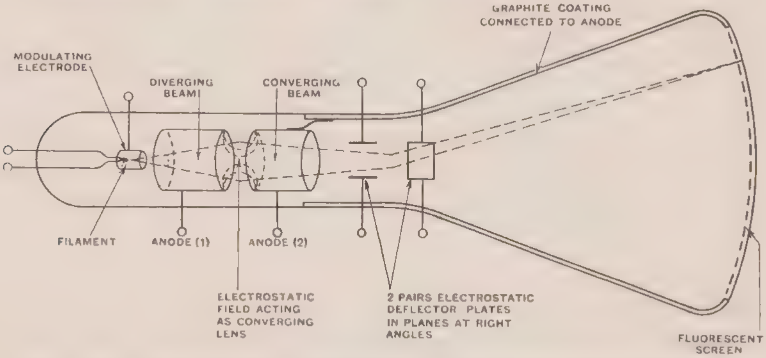


Fig. 108.—Diagrammatic representation of cathode ray tube, arranged for electrostatic focusing and scanning.

In some tubes an additional electrode is provided between the "Wehnelt" cylinder and the "focus anode" A_1. This provides an initial accelerating impetus and also operates in a similar manner to the screen grid of a screened tetrode by ensuring a constant electrostatic field in the "electron lens." Thus the "triode" characteristic and the load on the emitting cathode can be kept constant irrespective of the final anode voltage. The assembly which causes the acceleration and focusing of the beam is often called the *electron gun*. A diagrammatic representation of a typical tube is shown in Fig. 108.

High vacuum tubes—electromagnetic focusing.

An alternative method of focusing the beam in a vacuum cathode ray tube employs the principle of magnetic control of the electron beam. In this the tube is surrounded at the neck by a solenoid coil (Fig. 109).

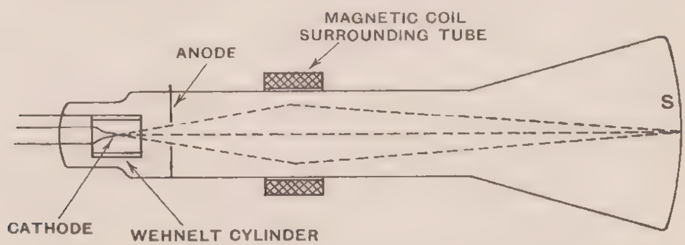


Fig. 109.—Diagram showing principle of magnetic focusing.

An electron entering the field of the coil will be caused to move in a spiral due to the magnetic force acting upon it, and to its axial velocity in the radial field outside the coil, so that when the electron emerges from the coil it is travelling towards

the axis, which it will meet at the " focus " point. Similarly all the electrons emerging from the anode aperture, are diverted into curved paths, and by correct location of the coil and correct adjustment of the magnetising current, these curved paths can be made such that the beam is brought to a focus at one point. The positioning of the solenoid with respect to the anode depends on the spot size required—the closer to the anode, the larger the diameter of the spot.

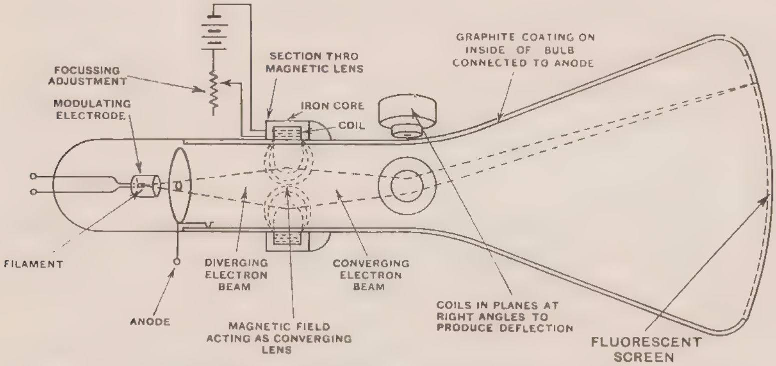


Fig. 110.—*Diagrammatic representation of cathode ray tube arranged for electromagnetic focusing and scanning.*

The advantages claimed for magnetic focusing are mainly bound up with the comparative simplicity of the tube construction, but a source of external power is required to energise the magnet. Fig. 110 shows a typical magnetic focus tube.

Gas focused tubes.

From early types of cathode ray tubes making use of a cold cathode and very high anode voltages emerged the " soft " cathode ray tube of the type often employed to-day. An electrode is introduced in the form of a cylinder enclosing the cathode, its object being to concentrate the electron stream leaving the cathode, and an inert gas (helium, neon, or argon) is introduced into the bulb. While passing from the cathode to the anode, the electrons ionise the gas molecules, and the positive ions being heavier than the electrons, their velocity is, therefore, much lower. These positive ions form a positive space charge in the centre of the electron ray and, because this charge exercises an attractive force on the electrons, the ray is concentrated.

The presence of gas serves two objects, to permit the use of comparatively low operating voltages, and to permit focusing of the beam. The gas focused type of tube is independent of frequency until the deflection velocity becomes great enough to interfere with the ionisation of the gas by electrons in the beam, but since the focusing depends upon the ionisation of the gas along the path of the beam, the focus becomes poor at high radio frequencies.

Modulation of the intensity of the beam also interferes with the focus. Such effects are not objectionable in many cases, such as in most oscillographic apparatus, but represent serious objections to other applications, such as where the C.R. tube is applied to apparatus calling for fine focus independent of modulation, and good H.F. response.

The focus is normally adjusted by control of the cathode temperature (in the case of a directly heated cathode, by the filament current), and this is usually kept

as low as consistent with obtaining a sharply focused spot. A typical gas focused tube is diagrammatically illustrated in Fig. 111.

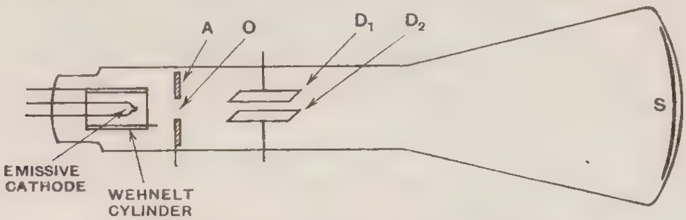


Fig. 111.—*Typical gas focused (soft) cathode ray tube. A—anode, O—orifice, D_1 D_2—deflector plates.*

The fluorescent screen.

The screen in a cathode ray tube is an essential feature of its operation and the nature of the screen will depend on the use to which the tube is to be put. For many years screens which have the property of fluorescence have been used in connection with X-ray apparatus. Applied to cathode ray tubes, the screen usually consists of a chemical powder deposited on the inner wall at the end of the tube, in such a way that the impinging electron discharge, focused by such methods as have been described, causes intense bombardment of the powder at high velocity at the point of impact. This gives rise to a spot of brightness which by suitable deflection control of the beam, can be made to move over the surface of the screen; the charge of accumulated electrons is normally allowed to leak back to cathode along the walls of the bulb.

Continued focused impact at one spot will cause " burning " of the screen material, resulting in a dark area at this point when the beam is moved or cut off; unless the spot is de-focused or reduced in intensity, *it is necessary to keep it moving continuously in order to prevent this burning.*

Movement of the spot, if of very slow speed, may be observed by the eye, but as the speed of travel across the screen increases, the eye, by persistence of vision, views the movement as a " trace " of light. It is the trace which makes the cathode ray tube valuable in viewing rapidly changing alternating potentials as they change in direction, phase, angle or intensity.

To meet an expanding field for the applications of the cathode ray tube, fluorescent screens having a variety of characteristics have been employed, the characteristics depending upon the chemical composition of the screen material. Such screens can be prepared to emit light of practically all colours ; green, white, blue or sepia being common. Again, the time taken for the glow to rise and fall depends upon the materials used ; a very actinic luminosity, but with a rapid fade, is useful in cases where we want a photographic record of the spot trace, while if a visual study or a photographic record of high speed transients is required, a long time period for the fade is desirable. This latter is termed the " afterglow " and its presence enables an oscillogram to be photographed after the transient phenomenon has ceased.

Deflection systems.

The deflection system in a cathode ray tube may take either of two forms ; it may be electrostatic or magnetic. Alternatively, it may take the form of a combination of the two.

We have seen how a beam of electrons emitted from the cathode may be formed and converted by means of the electron lens from a divergent to a convergent

beam, ultimately to be brought to a focus at the fluorescent screen forming a bright spot at the focal point. The object of the cathode ray tube, however, is to provide a visible means for observing voltage changes, and it is the movement of the bright spot on the screen which enables an analysis of the applied voltages to be made. Taking an analogy from light, a pencil of light may by refraction be deflected from a straight path by means of a prism ; similarly by a magnetic or electrostatic force the pencil of electrons may be deflected, causing the spot to move, such movement being in direction and extent dependent upon the force applied to the cathode beam.

Electrostatic deflection.

In this system it is usual to insert within the neck of the tube, and beyond the final accelerator electrode, two pairs of deflector plates placed a short distance apart, one pair being in a plane at right angles with respect to the other pair, Fig. 112(a).

Fig. 112(b) represents the effect on the electron beam of a voltage difference

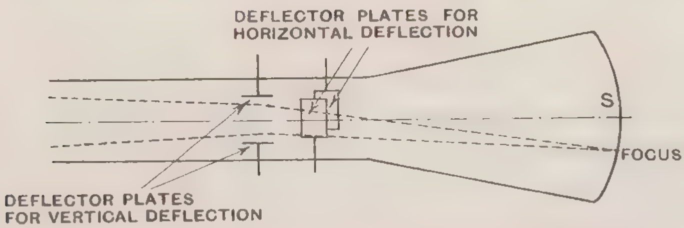


Fig. 112(a).—Deflection system in electrostatically deflected tube.

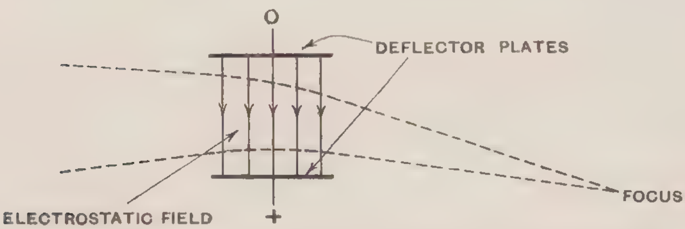


Fig. 112(b).—Deflection of the electron beam by an electrostatic field.

applied to one pair of plates, to deflect the spot on the screen in a vertical direction, resulting in a vertical straight line trace ; the effect of a voltage difference applied to the other pair of plates would be to deflect the spot in a horizontal direction, resulting in a horizontal straight line trace. The deflection is caused by the attraction of the electrons forming the beam towards the plate which is charged to a positive potential, and the repulsion resulting from a negative charge on the opposite plate. The two pairs of deflector plates may be independently controlled such that the spot may be made to take up any position on the screen, depending on the relative voltages applied to the plates, the final position being the resultant of two forces at right angles.

The deflection of the beam, with a given potential difference between the two plates is also a function of the voltage applied to the accelerator electrodes, and of the general arrangement of electrodes in the tube ; for a given design, the higher the accelerator voltage the greater force is required by the deflector plates to pull the electron beam from its normal line of travel.

The *sensitivity* of a tube is usually measured in terms of a constant K depending on the tube design divided by E (the final anode potential). Thus if the spot is deflected 1.0 mm. for 3 volts difference applied to a pair of deflector plates, when the final anode voltage is 500, then :

$$\frac{K}{500} = \frac{1}{3} \text{ mm. per volt. and K in this case} = 170 \text{ approx.}$$

$$\text{Sensitivity of tube} = \frac{170}{E} \text{ mm. per volt.}$$

Electrostatic deflection is often preferred owing to the low power required in the external circuits associated with the beam deflection ; as the forces applied are electrostatic, the current required in the deflector plate circuits is negligible, and a simplicity of control circuit results. The design of the tube itself is, however, elaborated by the inclusion of the two pairs of deflector plates, and an alternative method is to combine electrostatic and magnetic deflection, which is carried out in some tubes to meet particular operating conditions. A typical design of double electrostatically deflected tube was shown in Fig. 108.

Magnetic deflection.

Since the beam acts as a conductor carrying a current, the placing of a magnet near the tube will deflect it perpendicular to the field in a direction depending on the polarity. The usual method of deflection by magnetic fields is to bring in close proximity to the neck of the tube suitably designed electro-magnet coils (which may be air-cored or iron-cored) positioned immediately beyond the final accelerating electrode, that is, between the final anode and the fluorescent screen. The magnetic field, controlled by an outside source, can be thus made to move the electron beam at right angles to the axis of the field (Fig. 113). The greater the

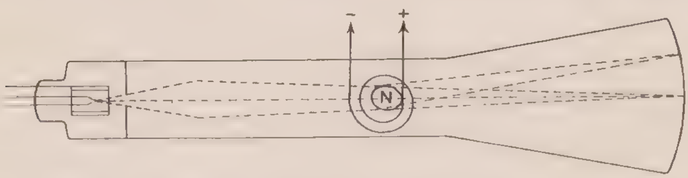


Fig. 113.—Deflection of the electron beam by a magnetic field. Illustration shows magnetic lines of force entering paper. (N pole above.)

strength of the field, the more will the beam be deflected from its straight path course, and hence the spot can be made to traverse the screen in a straight line, the amplitude of the trace being controlled by the current through the coil.

Similarly, a second electro-magnet with a transverse field at right angles to the former, may also be placed in close proximity to the tube, and this will, on being energised, deflect the electron beam in a plane at right angles. Thus the two magnetic fields, independently controlled, can be arranged to cause the spot to take up any position on the screen, according to the relative currents applied to the electro magnets, the final position being the resultant of two forces at right angles.

Such tubes have the advantage of comparative simplicity and economy of construction, although more power must be supplied from external sources for a given deflection than in the case of electrostatic deflection methods. The *magnetic sensitivity* with a given coil and coil disposition may be expressed in millimetres deflection at the screen, per ampere-turn. A typical design of electromagnetically deflected tube was shown in Fig. 110.

CHAPTER 14

The Cathode Ray Tube : Application.

The cathode ray tube is undoubtedly one of the most versatile pieces of electrical equipment for measurements, observation and recording of phenomena ever developed ; day by day further uses are being found for it, and it is convenient to divide its applications into three main groups :

(1) Laboratory measurements of voltage, frequency, phase relationship and the like ; examination of waveforms, valve characteristics, recording of transient phenomena, etc.

(2) Determining the extent of any variable quantity which may be transferable into terms of electrical voltage, for ease and rapidity of observation.
Examples of these are found in radio direction finding—to determine the angle between two incoming signals applied to directional frame receivers ; in electro-medicine—to record the nature and timing of heart beats and electrical impulses of a nerve.

(3) Building up of picture frames, composed and succeeding each other at speeds which by persistency of vision result in a moving picture sequence such as in television.

It is obviously impracticable, indeed it would be outside the aim of this review, to deal in any detail with methods of operating the tube beyond those which might be taken as fundamental in any of the above main heads.

Fig. 114.—*A small electrostatic cathode ray tube suitable for oscillographic work or general observation—Type* 4081A. *This tube has a 3-inch screen and works at* 800 *max. anode voltage.*

Fundamental principle of application.

As we have seen, the utility of the cathode ray tube depends on the ability to move the focused electron beam in any direction and velocity across the fluorescent screen ; this process is known as " scanning " or " sweeping " the screen. The relationship between the voltages applied

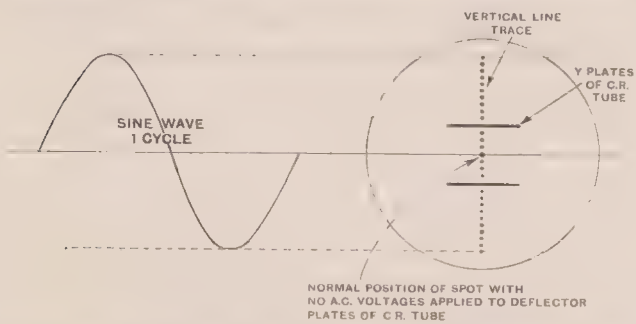
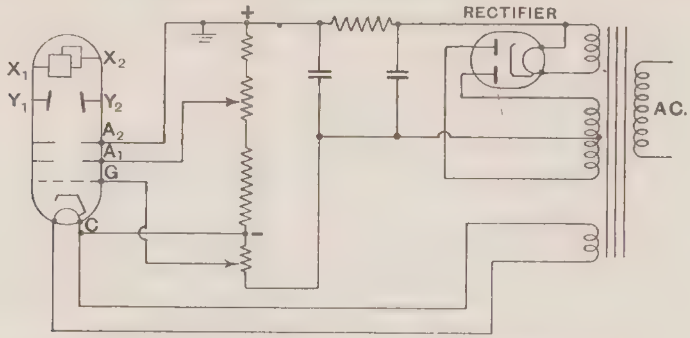


Fig. 115.—*A.C. voltage applied to one set of plates only—spot appears as a line trace.*

to the pair of electrostatic deflecting plates in an electrostatic deflection tube, or the current through the magnet system in a magnetic deflection tube, determines the movement of the spot, and the form of the visible " trace " from which certain results may be deduced.

In the case of the electrostatic deflection tube, the pair of plates giving horizontal deflection of the spot are commonly called the X plates, and those giving vertical deflection are called the Y plates.

A simple example is that of a very low frequency alternating sine wave voltage applied to one set of plates only (say the Y plates), the other set of plates being held



A_2—*Final accelerator " anode."*
A_1—*Focusing " anode."*
G—*Modulator electrode (grid) (" Wehnelt " cylinder).*
C—*Cathode.*
X_1 X_2—*Deflector plates.*
Y_1 Y_2—*Deflector plates.*

Fig. 116.—*Typical diagram for simple cathode ray tube circuit with provision for separate voltages to each pair of deflecting plates independently.*

at earth potential. This may be shown diagrammatically as in Fig. 115 where, since only one force is acting upon the electron beam, the field set up by the applied deflecting voltage is determined by the instantaneous amplitude of this applied voltage. Due to persistency of vision, the resultant spot movement appears as a vertical line of length corresponding to the peak amplitude of the applied voltage.

To make the spot trace out the shape of the applied waveform, a horizontal deflecting voltage is simultaneously required, which if the time taken to move the spot from one end of its traverse to the other exactly corresponds to the time taken for one complete cycle of the voltage applied to the Y plates, will reproduce a " trace " of one complete wave, of horizontal amplitude corresponding to the " sweep " voltage applied to the X plates. Methods of achieving such a " sweep " circuit will be briefly outlined later.

Fig. 116 indicates a simple circuit arrangement in which a cathode ray tube may be energised and utilised to demonstrate the phase difference, or frequency difference, between two alternating voltages applied to each pair of plates respectively.

The above example is for alternating voltages in the form of sine waves applied to each pair of plates. We must now consider what are perhaps the most common applications of the cathode ray tube, namely, the observation of the effect of applied voltages when these are not sinusoidal. In all such cases, means must be provided whereby the electron beam, being in one direction under the influence of the waveform to be observed, may be caused to move in the other direction at right angles in accordance with a predetermined *time base*. The " time-base " or *sweep circuit* must position the spot at a given point, move it across the screen at a known speed, and, in the shortest possible space of time return the spot to its original position, ready for a new sequence of events. The voltage applied to the time-base is referred to as the *sweep voltage* and the rate at which it moves the spot in a forward direction is referred to as the *sweep frequency*. The rapid return of the spot to its original

position is often referred to as the *flyback*, and the rate of this return as the *flyback speed*.

If we assume the movement of the spot along the X axis is linear, with a rapid " flyback " at the end of each traverse, an alternating voltage applied to the Y axis will appear as a wave trace, such as in Fig. 117(a), provided that the sweep frequency corresponds with the frequency of the wave under observation. If the sweep frequency is some submultiple of that of the wave under observation, several cycles of that wave will appear on the screen. In Fig. 117(b) the sweep frequency is one-third, giving three complete waveforms on the screen. The sweep voltage determines the lateral amplitude of the wave under observation—it is normally desirable for this to be of such a value that the observed trace occupies almost the whole available width of the screen.

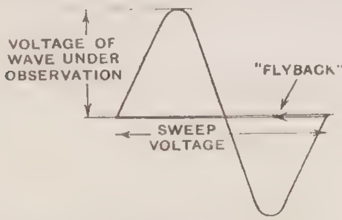


Fig. 117(a).—Sweep frequency equal to frequency of alternating voltage applied to Y plates.

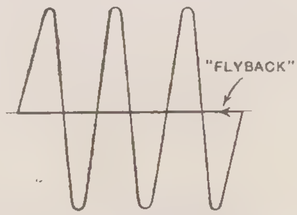


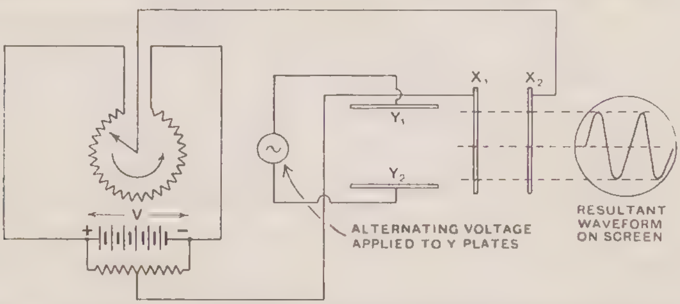
Fig. 117(b).—Sweep frequency one-third the frequency of alternating voltage applied to Y plates.

Synchronisation.

In order to preserve a stationary image of an observed waveform, on the screen, it is necessary that the sweep voltage be maintained at the same frequency or some submultiple of the frequency of the observed waveform. This may be done by feeding a small portion of the voltage to be observed to the input circuit of the sweep voltage oscillator, in order to control the frequency of the latter. The injection of this *synchronising pulse* keeps the sweep oscillator in step with the frequency of this pulse, and " locks " the image so that it appears stationary on the screen. Too great a synchronising voltage, however, may affect the frequency of the sweep circuit, and tend also to distort the observed pattern.

Essentials of time-base circuit.

A complete review of the cathode ray tube and its application necessitates a



Potentiometer arm rotating at half frequency of alternating voltage applied to Y plates.
V = voltage (amplitude) of sweep.
Fig. 118.—Simple time-base with potentiometer.

work devoted solely to this subject and such authoritative publications as are available contain also descriptions and circuits relating to various forms of time-base

circuits. A full appreciation of these is beyond the scope of this publication, but as an introduction to a study of the subject a brief description of a typical time-base and its requirements will be of interest.

The simplest time-base or sweep circuit would consist of a direct voltage applied to one pair of deflector plates, of uniformly increasing potential from zero to maximum, with an instantaneous return to zero at the end of its maximum amplitude. This, in its simplest form, could be arranged by means of a primary battery of suitable voltage and a potentiometer having a rotating arm to increase the voltage with a rapid return to the initial point at the end of each complete rotation (Fig. 118) (see page 97). If the speed of rotation of the potentiometer arm is sufficiently great, and the rotation is recurrent, the trace appears as a single line across the screen ; when an alternating voltage is simultaneously applied to the other pair of plates, the trace assumes the waveform of the applied alternating voltage.

Such a sweep may be more conveniently provided by means of an electronic device, such as a cold cathode neon glow tube, or by a valve or gasfilled relay. A simple method is that of a cold cathode neon glow tube in conjunction with a

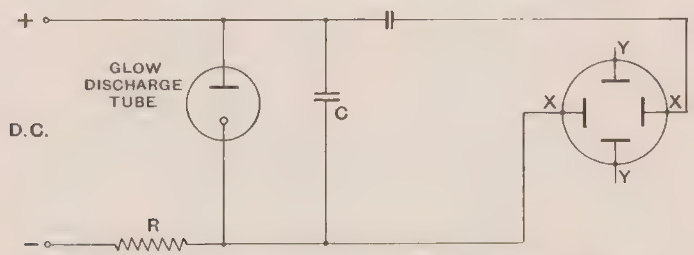


Fig. 119.—*Simple time-base with glow discharge tube.*

condenser and resistance and a source of direct voltage supply. Thus in Fig. 119 current from the D.C. source flows through a resistance R and charges condenser C. Across the condenser C is connected the glow discharge tube which will " strike " as soon as the voltage across the condenser C, and, therefore, across the tube electrodes attains sufficient value. As soon as this occurs, the gas contained in the tube is ionised, and the voltage across it will fall, discharging the condenser. At a lower voltage across the tube, ionisation ceases, the tube attains a very high resistance once more, and the cycle of operation is repeated.

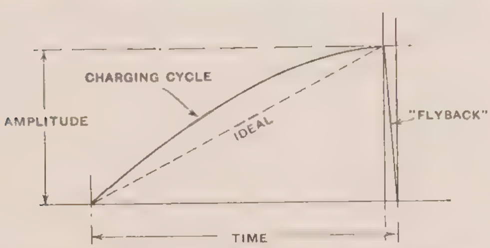


Fig. 120.—" *Saw-tooth* " *time-base. Showing departure from linearity in charging cycle using circuit in Fig.* 119.

The output from the tube may be connected across a pair of cathode ray tube deflecting plates, when the charging voltage across C will cause the spot to traverse the screen and the rapid discharge will return it to its original position. If the amplitude of the spot movement were plotted against time, the resulting characteristic would have the shape such as in Fig. 120. This, owing to the comparatively gradual rate of increase of charging voltage, and the almost immediate discharge, is known as a *saw tooth* time-base. The number of charging periods per second, or the frequency of the sweep, is a function of three circuit constants—the capacity C, the resistance R and the difference between " striking " and extinguishing voltages. The frequency is

inversely proportional to the capacity, inversely proportional to the resistance, and inversely proportional to the striking voltage.

"Linear" time-base using gasfilled relay.

It will be observed on referring to Fig. 120 that the charging cycle is not linear with respect to time, and the shape of the curve implies that the rate of movement of the spot across the screen will be reduced as its distance from the origin increases. This is due to the non-linear charging characteristic of a condenser. In practice, a forward movement of the spot at uniform velocity is desirable in order to avoid distortion of observed waveforms, and one method of achieving this will be described. Such a method is typical of commercial applications in which a limitation of sweep frequency to a maximum of about 10,000 cycles per second is no disadvantage, and it makes use of a thermionic valve (usually a pentode) in conjunction with a gasfilled relay. A typical circuit employing this principle is shown in Fig. 121.

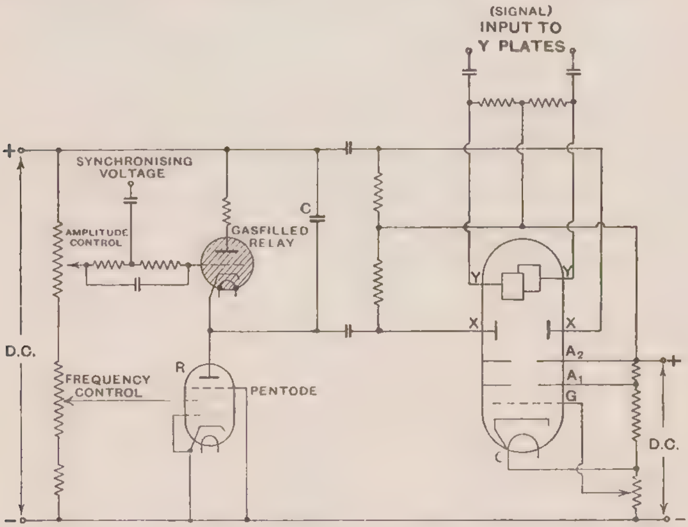


Fig. 121.—Schematic diagram showing time-base circuit for linear sweep voltage employing gasfilled relay and pentode valve in series which acts as limiting resistance R. Frequency controlled by condenser C and by screen voltage of R.

The pentode valve, connected as shown, takes the place of the resistance R in Fig. 119, and serves as a constant current device. The effect of the introduction of this valve in series with the charging condenser is to keep the flow of charging current constant during the entire charging cycle, and this maintains the rise of voltage across the condenser at a constant rate, resulting in a linear output to the deflecting plates. The current passed by the pentode may be controlled by its screen voltage, care being taken that the valve is operated over that part of its characteristic where its anode current is constant. The voltage across the condenser, therefore, increases linearly with respect to time, until it reaches a value at which the gasfilled relay can come into operation. This, of course, is when the ratio of anode to grid voltage of the relay exceeds the critical striking value. Immediately the gasfilled relay "strikes," the condenser is practically instantaneously discharged through the relay, which becomes de-ionised.

The point of the charging cycle at which discharge takes place may be controlled by the setting of a negative grid voltage applied to the gasfilled relay.

Good linearity is, however, only obtained if the setting of the relay grid voltage is such as to cause the glow discharge well before the maximum amplitude of the charging voltage. In this circuit the frequency of the sweep cycle is determined both by the value of charging condenser and by the screen voltage of the pentode, the latter serving as a variable resistance adjustable by screen voltage changes. In practice it is convenient to fix the value of the condenser (or utilise a number of alternative fixed condensers), which limits the frequency range covered by the screen voltage variation, but enables complete frequency coverage to be obtained in a series of steps.

The importance of synchronisation has already been referred to. In the circuit of Fig. 121 a small voltage may be applied to the grid of the gasfilled relay, and if injected at a point on the sweep cycle almost coinciding with the peak of the charge, it will give to the grid a small extra voltage, and this, combined with the rising anode voltage, is sufficient to cause the relay to " strike " at regular time intervals and so prevent " drift " of sweep frequency. The synchronising pulse may be fed into the circuit through a transformer or by resistance capacity coupling from the voltage of the source being observed, or from an external source.

" Hard " valve time-base.

There are several alternative types of saw tooth wave generators, some of which employ hard vacuum valves throughout and are thus more suitable where sweep frequencies higher than 10,000 cycles per second are required. Such circuits are fully dealt with in publications devoted to applications of the cathode ray tube. An example of a hard valve time-base circuit is given in Fig. 122.

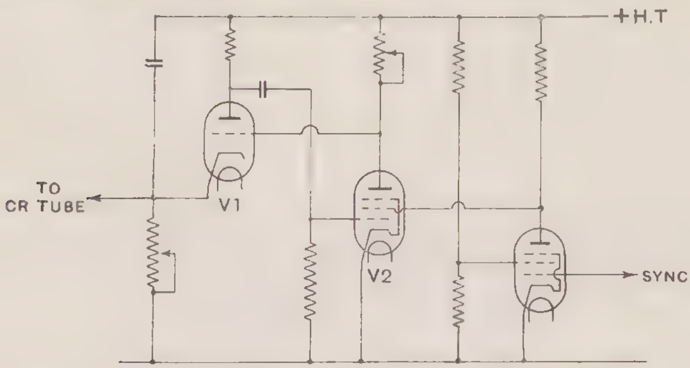


Fig. 122.—Typical hard valve time-base circuit suitable for high frequencies up to 1 megacycle or more.

Power supply to C.R. tube.

A typical circuit arrangement for supplying the voltage, positive or negative, required by the various electrodes of a cathode ray tube is given in Fig. 123. The actual values of the resistance components will vary for different tubes, but in essence the principle of the circuit remains constant. The arrangement shown is for a 4081A 3-inch tube using a U17 rectifier to deliver 800 volts to the C.R. tube " gun." It is convenient for the positive H.T. supply line to be earthed in the case of power supplies for C.R. tubes of this nature.

Spot shift.

For many applications, it is desirable to locate the spot centrally on the screen before applying the deflecting voltages (care being taken to reduce brightness when

the spot is stationary, to avoid screen burning). It sometimes happens that the stationary spot requires to be moved horizontally or vertically, and this may conveniently be done applying a small D.C. polarising voltage to one or both of the deflecting plates, as in Fig. 124, until the required positioning is attained.

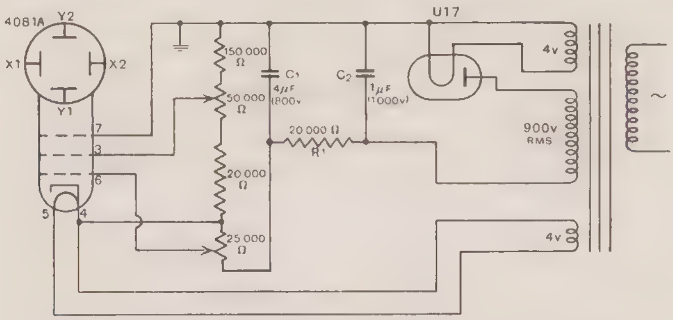


Fig. 123.—Typical circuit showing high voltage power supply to 4081A cathode ray tube. Electrolytic condensers (if used) should have insulated terminals. The mains transformer should be designed with adequate insulation between windings.

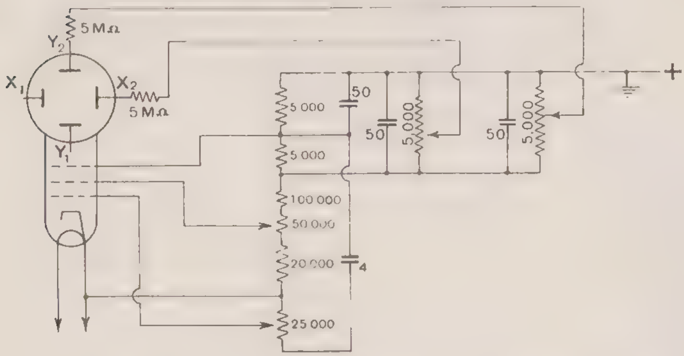


Fig. 124.—Typical " shift " circuit applied to C.R. tube power supply.

CHAPTER 15

Current Stabilisers : Voltage Stabilisers.

Although not coming within the scope of " Valves " or " Thermionic Tubes," brief mention may be made before the conclusion of this review to devices which are commonly utilised in practice for current or voltage stabilisation. The application of these is not always fully understood, nor the distinction between the relative functions of commercial devices supplied to meet these needs, and so we shall in this chapter briefly examine two classes of device in general use.

Current stabilisers—the Barretter.

Current stabilisers are always used in series with the " load " and source of power supply. One way of adjusting the current through a given load is by the insertion of a resistance of suitable value in the supply leads ; such a resistance may be fixed or variable, and in common practice consists of resistance wire, or a compressed powder of carbon or graphite. These forms of resistance element are chosen so as to provide a given voltage drop across them, according to their resistance

and the current passing, the voltage drop being (for a given set of conditions) proportional to the current, within the limits of current carrying capacity of the resistance element. Thus in these cases a resistance-temperature coefficient of a low value is a desirable feature in the material chosen. (This means that within the range of the working conditions, the resistance of the element is for all practical purposes unaffected by temperature changes.)

To take the case of a wire resistance in series with a given load, the current through the load and resistance will depend upon the value of the total resistance in the circuit and the voltage of the supply—when the supply voltage varies so will the current through the circuit, unless the total resistance is changed at the same time to compensate for the variation. Such changes in resistance may be made manually by means of taps or sliders in the case of a wire element, but it is often necessary for such adjustments to become automatic in action, in cases where the maintenance of " constant current " is desired over a range of supply voltages. One device commonly made use of to achieve this result is termed a *barretter*.

Constant current can be achieved if a substantially constant voltage drop across the load is maintained despite changes in applied voltage, and the extent to which this may be possible will depend upon the " temperature coefficient " of the resistance element, or in other words, the extent to which its resistance changes with temperature. If its resistance *increases* with rising temperature, this will cause an increasing voltage drop across it as the current, and therefore temperature, tends to increase, and so will automatically offset the rising current.

Fig. 125.—Typical iron wire barretter.

Certain metals achieve this object to a greater extent than others, and in a barretter the resistance element usually takes the form of very pure iron, drawn to a fine wire, which, it is found, displays the property so desirable for this purpose, *if operated within a given range of temperatures.* To prevent oxidation and rapid " burn out " at the temperatures of use, the wire is enclosed within a bulb from which the air has been removed, but as it is also necessary that the heat generated in the iron resistance wire should be quickly conducted away, the wire is contained in an atmosphere of a suitable gas which has the property of rapidly removing the heat, and which at the same time will not attack the metallic element. Such a gas is hydrogen, and so the commercial barretter consists of an iron wire, of suitable length and drawn to a suitable diameter, surrounded by hydrogen gas at a given pressure and the whole enclosed within a glass bulb (Fig. 125).

Characteristics of barretter.

The characteristic of a typical barretter is shown in Fig. 126 where it will be seen that as the voltage across it is increased, there is a rise in current which becomes progressively less until a region of approximate constancy is reached (corresponding to a rising resistance) after which current again increases and would continue to do so were the voltage still further raised, until the barretter was destroyed. The range of voltage across which the rising current characteristic is least steep (or approximately flat) is called the working or " barretting " range of the barretter. This will vary with different designs and with the degree of current stabilisation desired ; the voltage corresponding to the lowest working current is often called the " ground voltage."

When cold, the resistance of the barretter is much lower than when hot, and there is thus at first a tendency towards a " surge " of current; the current only becomes constant when the iron filament and surrounding gas have had time to settle down to stable conditions. The use of hydrogen, which is a very light and mobile gas, greatly helps in speeding up the stabilisation of operating conditions. (Certain compensating devices are sometimes used in series with the barretter and load to offset this initial surge of current, but their utility is only apparent when the nature of the circuit is such that it is endangered by these brief current surges.)

Different types of barretters can conveniently be made for control of currents from approximately 0.2 ampere up to several amperes, the lower current limit being usually determined by difficulties in manufacture (small wire diameters) and the higher by restrictions in physical size due to excessive wattage to be dissipated in the tube.

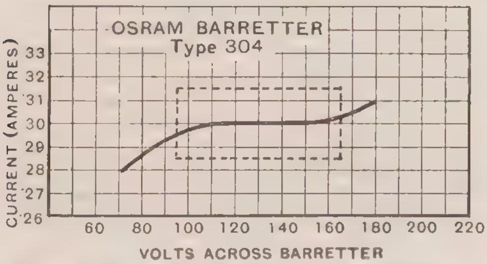


Fig. 126.—Typical voltage-current characteristic of barretter. Example shows current control at 0.3 amp. over a voltage range of 95/165 volts.

In operation, the barretter is inserted in series with the available voltage and the " load," as in Fig. 127, and is chosen to be of a type with suitable current capacity, voltage range, and " ground voltage " for the conditions of application. When used to stabilise the current through valve filaments or heaters, it should be wired in circuit at a point in the heater chain most near to the positive mains terminal if D.C. is the source of supply. In radio and audio frequency amplifiers, the barretter does not usually control the " H.T. " current.

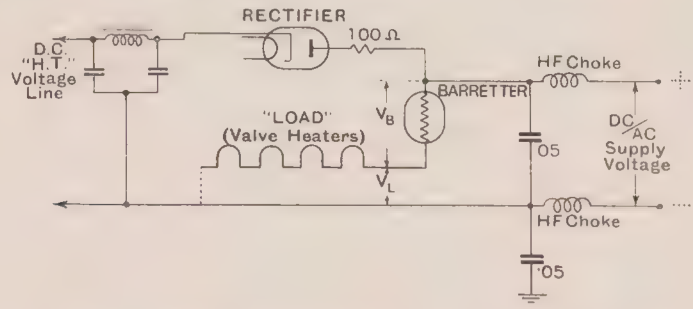


Fig. 127.—Typical circuit illustrating use of " barretter " in series with valve heater load, to maintain substantially constant current with varying D.C./A.C. supply voltage.

Precautions to be taken when using barretters.

1. It is necessary to remember that a barretter, by its very nature, is bound to be wasteful, and it is found in practice that for a useful voltage V_L applied across the load (Fig. 127), a voltage V_B must be dropped across the barretter, where V_B is not lower than V_L, and may be as high as $2V_L$. In a practical case in a radio set, with a mains voltage of 240 volts, and a voltage across the valve heaters in series of, say, 80 volts, then 160 volts (i.e., twice the total valve heater voltage) will be wasted across the barretter.

2. A barretter is not an instantaneously operating device, and a minute or two is usually necessary to allow the circuit to settle to its steady current value.

3. A current surge (often greatly exceeding the steady current condition) occurs at the moment of switching on, owing to the fact that the barretter (and often also the load) is cold to start with.

4. It is important that a barretter should not be mounted in close proximity to a strong magnetic field, such as that from a loud speaker or smoothing choke. The effect of a strong magnetic field may give rise to noise in operation, and due to the use of iron wire, excessive magnetic vibration may be set up in the barretter filament which may in extreme cases result in short life.

5. Care should be taken in handling, as the bulb becomes very hot in operation, and remains so for some time after the current is switched off.

6. In operation, ample air circulation should be allowed round a barretter, as the working bulb temperature influences the barretting current level.

7. It is preferable for a barretter to be mounted in a vertical position, cap down.

Voltage stabilisers—the neon tube.

The simplest method of obtaining constancy of voltage across a circuit within given limits of current is to utilise the properties of a gas discharge tube, such as a cold cathode neon tube. To see how this control can operate it is necessary to examine the characteristic of such a tube under conditions of varying applied voltage.

A device of this kind, as we saw in an earlier chapter, operates as an insulator until, with a steadily rising voltage applied across it, a point is reached at which the voltage is sufficient to ionise the neon gas atoms, and the tube " strikes," resulting in the passage of current through the tube, and a sudden fall in voltage across it. With the normal commercial type of neon tube, this striking voltage occurs at about 170 volts, and the direct application of this voltage without the interposition of a protective limiting resistance would result in the immediate destruction of the tube, since the gas discharge current has the same " negative resistance " characteristic as that of an electric arc. To prevent this, commercial tubes, such as the

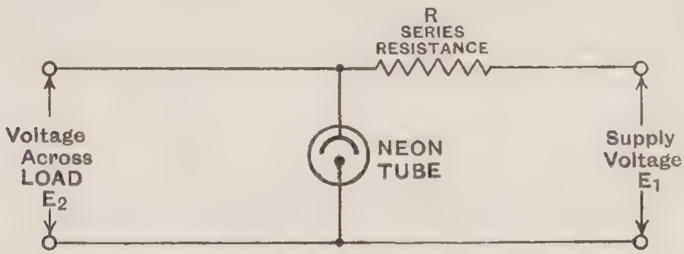


Fig. 128.—Circuit illustrating method of voltage control by means of neon tube.

" Osglim " tube are made with the necessary resistance permanently incorporated in series (fitted inside the cap) and this resistance limits the current and so allows the tube to be used across the normal electric supply mains voltages up to 250 volts.

If in such a tube arrangements can be made to separate the tube from its associated resistance, it will be found that within given limits of current, depending on the design of tube, the voltage across the tube alone will remain substantially constant.

Such an arrangement is shown in Fig. 128, where E_1 is the applied voltage, E_2 the voltage across the tube and R the indispensable series resistance. The output

voltage E_2 is equal to the input voltage E_1, less the voltage drop across R. If there were no load connected across E_2, then E_2 would rise as E_1 is increased, until the " striking " voltage is attained, at which point the discharge takes place, and then it will be found that E_2 will fall to about 150 volts, the difference of about 20 volts appearing across the resistance R. As the applied voltage E_1 is further raised, the current through the tube will increase, but E_2 will remain at approximately 150 volts, the voltage across R increasing due to the rising current through it. R is so chosen that the maximum rise in E_1 will not cause an excessive current through the tube. If now a load is connected across E_2, the current through the tube will decrease by the amount of the load current, and the total current will remain constant. Therefore, the voltage drop across R is unaltered and E_2 remains constant.

Thus a neon tube so connected can be used to stabilise the voltage across a load despite changes in applied voltage, at a mean voltage of the order of 120 volts, and within limits of load currents dependent upon the design of tube (electrode shape and dimensions, gas pressure, etc.) This is the simplest form of voltage stabiliser (Fig. 129). It will be noted that, as with a barretter, this device also is wasteful, as a considerable fraction of the total current is not used in the load, but is shunted through the stabiliser tube.

Fig. 129.

Typical neon voltage stabiliser tube, single element type. Operating voltage : 120 *volts (approx.). Control current :* 0–40*mA.*

Tubes have been constructed with several electrodes so arranged that different stabilised voltages may be available—the tube then acting as a form of stabilised potentiometer. An example of this is the " Stabilovolt " tube illustrated in Fig. 130.

Fig. 130.

The " Stabilovolt " tube. In this tube stabilisation of voltage is obtained for various voltages between the several electrodes.

Neon tubes used as voltage stabilisers depend for their consistency of operation largely upon the manufacturing processes employed in production of their electrodes, and upon the gasfilling. By specialised manufacturing methods tubes have been made for a particular application to strike at voltages below 100 volts. Control of " striking " and stabilised voltage is achieved by the use of activated cathodes and special mixtures of gases for the gasfilling. The " Stabilovolt " tube is an example of these processes being applied, as is also the single element activated cathode tube illustrated in Fig. 129.

With loads not exceeding some 10 mA, a useful degree of stabilisation can be obtained by employing the commercial " Osglim " lamp with its resistance removed from the cap, and wired separately into the circuit in the manner previously described (Fig. 128), but in this case the uniformity of " striking " voltage, and running voltage found in different lamps is likely to be worse than that of neon tubes specially designed to act as voltage stabilisers.

A number of stabiliser tubes such as the type shown in Fig 129 may be wired in series, if desired to " take off " stabilised voltages in approx. 120 volt steps from an applied voltage substantially higher in value, provided that each tube is shunted by a high resistance of the order of 200,000 ohms to ensure the uniform " striking " of each component tube in the chain. Neon stabilisers cannot

be wired in parallel to increase the load current, unless each has its own associated series resistance R (Fig. 128) in which case each tube controls its own associated circuit independently.

CONCLUSION

The conclusion to this review will be for most readers only the preface to further study and work on some particular application of valves or cathode ray tubes which they are specially called upon to pursue.

The thermionic valve is probably associated most closely with applications within the field of radio operations, with voltage or power amplification at radio or audio frequencies, or with rectification of alternating voltages and currents. The applications of the valve, however, by no means end with such fields, and a large number of specialised designs have been introduced, aimed principally at industrial or laboratory applications. Problems associated with industrial applications or laboratory investigation using valves or cathode ray tubes usually have an individual character, but there are many requirements which can be met by a type of standardised design for a particular function.

It has obviously been impossible to enter into matters of mathematical or circuit detail on any one aspect of this vast subject, nor to deal with special problems of transmitting circuits, but if a grasp of the fundamental principles behind certain features of design or usage has been made possible to the reader from the necessarily sketchy survey of some of those more commonly met with in daily use, then the object of this publication will have been achieved.

The writer has purposely avoided the inclusion of a large number of circuits, as few of these would be of practical value in any particular case, and the reader is therefore referred, from now on, to other and more detailed works dealing with his own specialised branch of application. In addition, descriptions and illustrations of specialised types of valves, which it is possible the reader will be called upon to handle, are of necessity omitted from inclusion at the time of publication.

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B	Book
J.I.E.E.	Journal of the Institution of Electrical Engineers (England)
W.E.	Wireless Engineer (*formerly* Experimental and Wireless Engineer) (Iliffe & Sons, Ltd.)
W.W.	Wireless World (Iliffe & Sons, Ltd.)
G.E.C. Journal	(The General Electric Co., Ltd., England)
H.M.S.O.	His Majesty's Stationery Office
Proc.I.R.E.	Proceedings of the Institute of Radio Engineers (America)
A.I.E.E.	American Institute of Electrical Engineers (America)
B.S.T.J.	Bell System Technical Journal (America)
G.E. Review	General Electric Review (The G.E., America)
Rad. Eng.	" Radio Engineering " (America)
Phys. Rev.	Physical Review (America)
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APPENDIX 1

Common Symbols applied to Valve Circuits.

I or i	Current (direct or alternating, usually amperes unless otherwise stated).
mA	Milliamperes (amperes $\times 10^{-3}$).
μA	Microamperes (amperes $\times 10^{-6}$).
mV	Millivolts (volts $\times 10^{-3}$).
μV	Microvolts (volts $\times 10^{-6}$).
kV	Kilovolts (volts $\times 10^{3}$).
E or e	Voltage (direct or alternating).
R	Resistance (ohms).
Ω	Ohms.
MΩ	Megohms (ohms $\times 10^{6}$).
W	Watts (in D.C. circuits = volts $\times$ amperes). also = I^2R
kW	Kilowatts (watts $\times 10^{3}$).
C	Capacitance or capacity.
μF	Microfarads (capacity in farads $\times 10^{-6}$).
$\mu\mu$F	Micro-microfarads (capacity in farads $\times 10^{-12}$).
L	Inductance (henries).
Z	Impedance of reactive circuit.
M	Mutual inductance.
f	Frequency (usually in cycles per second unless otherwise stated).
kc/s	Frequency in kilocycles per second.
mc/s	„ „ megacycles per second
π (pi)	3.14 approx., or $\frac{22}{7}$
ω (omega)	as $2\pi f$ = angular velocity (sometimes ω is used to indicate resistance in ohms).
m	Amplification factor of valve (sometimes mu).
E_F	Applied filament or heater voltage.
E_G	Applied D.C. grid voltage.
E_A	Applied D.C. anode voltage.
E_S	Applied screen voltage.
I_A	Anode current (usually milliamperes).
I_F	Filament or heater current (usually amperes).
I_G	Grid current (usually microamperes).
I_S	Screen current (usually milliamperes).
R_A	Anode impedance or " differential resistance " of valve.
R_L	Load impedance in valve anode circuit.
mA/volt (or g)	Mutual conductance of valve (milliamperes per volt).

R.M.S.	Root-mean-square ($\frac{1}{\sqrt{2}} \times$ peak value). The square root of the mean value of the squares of all the different values the A.C. can take during a complete cycle. The R.M.S. value represents the equivalent in heating effect to D.C. having the same value as the R.M.S. value.
LF or AF	Low frequency or audio frequency (50 to 15,000 cycles per sec. approx.).
HF or RF	High frequency or radio frequency (10^5 to 10^7 cycles per sec.).
U.H.F.	Ultra high frequency (over 10^7 cycles per sec.).
IF	Intermediate or supersonic frequency (100,000 to 500,000 cycles per sec.).
λ (lambda)	Wavelength in metres.

APPENDIX 2

Useful Formulæ.

Ohms Law $\quad I = \frac{E}{R} \begin{cases} \text{I in amperes.} \\ \text{E in volts.} \\ \text{R in ohms.} \end{cases}$ (applicable in D.C. circuits).

Power (watts) $= EI = I^2R$ (applicable in D.C. circuits).

Inductive reactance $= 2\pi fL$ (L in henries, f in cycles per sec.).

Capacitative reactance $= \frac{1}{2\pi fC}$ (C in *farads*).

Resonant frequency (cycles per sec.) $= \frac{1}{2\pi\sqrt{LC}}$ (L in henries, C in farads),

$= \frac{10^6}{2\pi\sqrt{LC}}$ (L in microhenries, C in microfarads).

Impedance $= Z = \sqrt{R^2 + X^2}$ (X is the reactance).

Wavelength (metres) $\lambda = \frac{300{,}000}{f}$ (f in kilocycles per sec.).

$= \frac{300}{f}$ (f in megacycles per sec.).

Wavelength (metres) λ of oscillatory circuit $= 1885\sqrt{LC}$ (L in microhenries, C in microfarads).

Amplification of valve circuit $= \frac{m \times R_L}{R_L + R_A}$ for resistive load,

$= \frac{m \times 2\pi fL}{\sqrt{R_A^2 + (2\pi fL)^2}}$ for inductive load,

Power developed in valve load (R.M.S.) $= \frac{e_L^2}{R_L}$ where e_L is R.M.S. voltage across load R_L.

The "Decibel": If two powers P_1 and P_2 are compared, then P_1 is said to show $10 \times \log_{10} \frac{P_1}{P_2}$ decibels gain or loss over P_2, according as P_1 is greater or less than P_2.

If two currents I_1 and I_2, or voltages E_1 and E_2 are being compared, then I_1 or E_1 are said to show $20 \times \log_{10} \frac{I_1}{I_2}$ or $20 \times \log_{10} \frac{E_1}{E_2}$ decibels gains or loss over I_2 or E_2 respectively, according as I_1 or E_1 are greater or less than I_2 or E_2.

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